TP6306E

HYBRID VEHICLES

A DESIGN STUDY OF PROPULSION SYSTEMS FOR A HYBRID VEHICLE

PREPARED FOR
TRANSPORTATION DEVELOPMENT CENTRE
(TDC)
MONTREAL

BY
MARATHON ELECTRIC VEHICLES INC.
MONTREAL

MARCH 1985

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by

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Montreal, P.Q.

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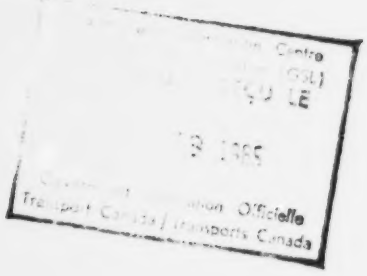
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17. Abstract

The purpose of this report is to document:

1) the design considerations of a propulsion system employing a heat engine and an electric motor for use in an on-road vehicle capable of accommodating four passengers plus some cargo, the vehicle complying with all applicable Canadian Motor Vehicle Safety Standards;

2) the projected fossil fuel saving possibilities of such a vehicle; and,

3) the estimated annual operating cost and the manufacturing cost of such a vehicle.

While a hybrid propulsion system for a vehicle of the size and capability considered would appear to offer substantial fossil fuel savings, the manufacturing and the operating cost estimates were such that the vehicle would not be economically feasible.

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17. Résume

Ce rapport présente:

a) les caractéristiques techniques d'un groupe motopropulseur combinant un moteur thermique et un moteur électrique pour la traction d'un véhicule routier 4 places, plus compartiment à bagages, et répondant à toutes les normes de sécurité de la loi canadienne sur la sécurité des véhicules automobiles;

b) les chiffres concernant les économies d'hydrocarbures autorisées par ce véhicule; et

c) les prix de revient et le coût annuel d'exploitation estimatifs de ce véhicule.

Le groupe motopropulseur hybride de véhicule considéré autoriserait d'importantes économies d'hydrocarbures, mais il n'est pas intéressant économiquement, vu un prix de revient et un coût d'exploitation beaucoup trop élevés.

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1. INTRODUCTION

1.1 Background

Consistent with the objectives of the National Energy Program for Canada which seeks to eliminate oil imports by 1990 and calls for zero growth in the use of oil-based transportation fuels over the next decade, the Transportation Development Centre, through Supply and Services Canada, issued contracts, in 1980 and 1981 to Marathon Electric Vehicles Inc. of Montreal to design and install two hybrid propulsion systems (one "series" and the other "parallel") in two standard Marathon C-360 electric vans. These were simplistic "proof-of-principle" systems and are described in Transport Canada Report numbers TP3765E and TP4229E.*

As a result of the above and Transport Canada's interest in further probing the potential oil fuel savings of hybrid propulsion systems for on-road vehicles, Marathon submitted in 1982 an unsolicited proposal to Supply and Services Canada titled "The Development of a Hybrid Passenger Cargo Vehicle". This resulted in the issuance of Supply and Services Canada contract number 10SD.T8200-1-1567 dated May 26, 1982, which is the subject of this report.

1.2 Objective

The Work Statement of contract #10SD.T8200-1-1567 is divided into two parts - "Design Concept Study" (Phase I) and "Propulsion System Development" (Phase II). The objective of Phase I was to design a hybrid propulsion system employing an electric motor powered by an on-board battery pack, a heat engine and suitable control mechanisms for installation in a lightweight on-road vehicle having a carrying capacity of 350 to 500 kg and which would be used in urban and suburban driving patterns. The vehicle so equipped would have to provide a cost effective, low oil-fuel consumption means of transportation and meet all applicable Canadian Motor Vehicle Safety Standards. If the Phase I study indicated that the basic criteria (cost effectiveness, low fossil fuel consumption and CMVSS compliance) of the hybrid propulsion system vehicle could be met then the objective of Phase II was to fabricate a "test bed" pre-prototype hybrid drive system using state of the art technology and available automotive componentry. This unit would then be subjected to laboratory testing in order to validate its anticipated operating characteristics.

*3765E Design, Fabrication and Testing of a Marathon C-360 Parallel Hybrid
4229E Design, Fabrication and Testing of a Marathon C-360 Series Hybrid

Although not included in the aforementioned contract, the Marathon unsolicited proposal contained an outline of possible subsequent development phases which would have led eventually to the production of a small fleet of hybrid powered vehicles for extensive field testing and evaluation.

2. CONCLUSIONS AND RECOMMENDATIONS

From a number of candidate vehicles the Chrysler T-115 van (marketed as the Dodge Caravan and the Plymouth Voyageur) was selected as the vehicle most suitable for conversion to a hybrid propulsion system and its specifications and characteristics were used in calculations of anticipated performance, fuel consumption, operating cost and conversion cost.

While a hybrid propulsion system appeared to offer substantial potential oil based fuel savings in certain driving patterns the projected operating costs and the estimated cost of conversion were such that, when compared to a standard gasoline engine T-115, the hybrid vehicle was economically not realistic. (Section 10, Table 10-2)

In urban use the hybrid equipped vehicle has a potential gasoline fuel saving in the range of 40% to 80% but, dependent on production volume, user capital cost (or leasing cost) would be 50% to 140% over the cost of a standard vehicle, the increased costs being due primarily to the high cost of the required dual power system and relatively low anticipated volumes. Estimated annual operating cost of the hybrid vehicle, including depreciation and using average 1984 energy prices, appears to be up to double that of the standard vehicle dependent on the driving patterns to which it is subjected.

Hybrid powered vehicles offer a reduced requirement for fossil based fuels in some areas of the ground transport sector. However, to be competitive in the marketplace, they would not only have to offer all of the safety features of a standard gasoline powered vehicle and most of the performance and convenience features, but also be cost effective both in terms of initial capital cost and operating cost. As indicated in Sect. 10, both of these costs are projected as being too high to make the hybrid vehicle economically feasible. Even if gasoline pump prices were 60% higher than average 1984 prices, the hybrid vehicle would still be more costly to operate than its standard gosoline counterpart.

In addition to its high capital and operating costs, two other major factors contribute to the negative appeal of the hybrid vehicle:

- the current world "glut" of fossil based fuels resulting in relatively stable, if not decreasing, gasoline prices and therefore little or no marketplace concern regarding fossil fuel conservation, and,

- no significant near term progress in battery technology which would produce improved energy storage capabilities and power-to-weight ratios. Considerable battery research has been, and continues to be, undertaken both in the private and the public sectors but economically acceptable improvements have not yet been forthcoming.

In view of the above it was the recommendation of the contractor not to proceed with Phase II.

During the Phase I work a considerable amount of reference and background material was accumulated which would be of value to any future examination of hybrid vehicle potential and is therefore incorporated in this report. For the same reason the descriptions and preliminary designs for computer based vehicle performance simulation techniques and for microprocessor based propulsion control systems are included.

3. DESIGN APPROACH

3.1 Methodology

This study was the first phase of a multi-phase program to design and develop an advanced hybrid vehicle which would provide a cost effective, low fossil fuel consumption means of urban and suburban transportation.

In approaching the task, effort has been concentrated on producing an advanced vehicle system, making use of sub-systems and components which will be fully developed and commercially available within the appropriate time frame. Where developmental items have been proposed for the system a suitable back-up production unit has been identified. This philosophy has not restricted, in any way, the examination of state of art componentry and, in developing the design, every effort has been made to ensure that the system will accept components of advanced design as these become available during the production life of the vehicle.

The study examines the requirement for a vehicle of the type proposed and typical production vehicles suitable for development to meet the performance specification are identified at an early stage. The propulsion system is designed to develop the full potential of the selected vehicle without exceeding the manufacturers gross vehicle weight, axle loadings or other key performance parameters which might reduce its reliability or safety. The selected vehicle thus provides a subsystem known to be reliable and to need no futher development.

Several alternative propulsion systems were examined and their performance in the selected vehicle predicted using hybrid vehicle computer simulation programs (HYVEC) as described in Appendix D. The components for the most suitable configuration were selected after examination of both state of art and commercially available alternatives. Conceptual designs for a micro-processor based control system were prepared and further computer simulations were carried out to confirm the performance predictions and establish the economics of operation. The operation characteristics of the hybrid vehicle were reviewed against the Canadian Motor Vehicle Safety Standards to ensure that the requirements were met.

3.2 General Requirement

The review of somewhat limited data produced by surveys of user requirements and observation of the usage pattern of light vehicles in the Montreal and Ottawa urban areas leads to the conclusion that there is a requirement for a

light vehicle capable of carrying loads up to 500 kg on urban and suburban roads. Typical applications are:

- Service vehicles, normally carrying an operator and tools and equipment for servicing domestic or industrial eguipment and appliances. Typical users in this category are Bell Canada, Hydro, Gas and other utilities and domestic appliance servicing contractors.

- Light delivery vehicles, normally carrying an operator and light cargo. Typical users are the Postal Service, Courier Services, retail store operators and food and catering service suppliers.

- Commercial passenger vehicles for local carriage of passengers and baggage within a city, or major installations such as airports, industrial complexes, entertainment, exhibition and retirement residential sites.

These roles are currently undertaken by a range of panel trucks, carry-alls or pick-up trucks with 500 - 1000 kg payload capacity. In keeping with current North American down-sizing philosophy a range of light trucks with payload capacities from 450 - 800 kg has been introduced recently and many operators are using these light, more economical units.

In fixing the basic payload capacity of the hybrid vehicle it is noted that many of the current vehicles are used well below their total payload capacity and that most of the tasks which have been identified could be carried out by a vehicle having a payload in the region of 350 kg. Increasing this to 500 kg would allow the vehicle to compete directly with the 1/2 ton truck and widen its application to some extent.

The cargo volume should lie in the same range as the competing conventional vehicles which is between 1.25 and 2.0 m^3. It is important, however, that the vehicle body should also be capable of providing comfortable seating for the driver and three passengers on occasion when it is used as a passenger vehicle.

3.3 Performance Requirements

3.3.1 Maximum Speed

The applications for which the vehicle is intended are found in urban and suburban areas and it is in this

environment that the vehicle will operate. There will be extensive operation over urban roads with speed limits of 50 or 60 km/h with limited operation on suburban highways with speed limits set at 80 km/h and occasional short journeys on expressways with speed limits of 100 km/h. While it is of primary concern that the vehicle should be as economical as possible in the urban environment it must also be capable of operating safely in highway and expressway traffic. To achieve this it must be capable of cruising at 85 km/h: an additional 10 km/h is desirable.

3.3.2 Acceleration

For safety the vehicle must be able to overtake on an urban highway within the sight distances which are provided. The following table shows the sight distances currently specified for Canadian roads.

Figure 3.1

Minimium Passing Sight Distances, Canadian Roads

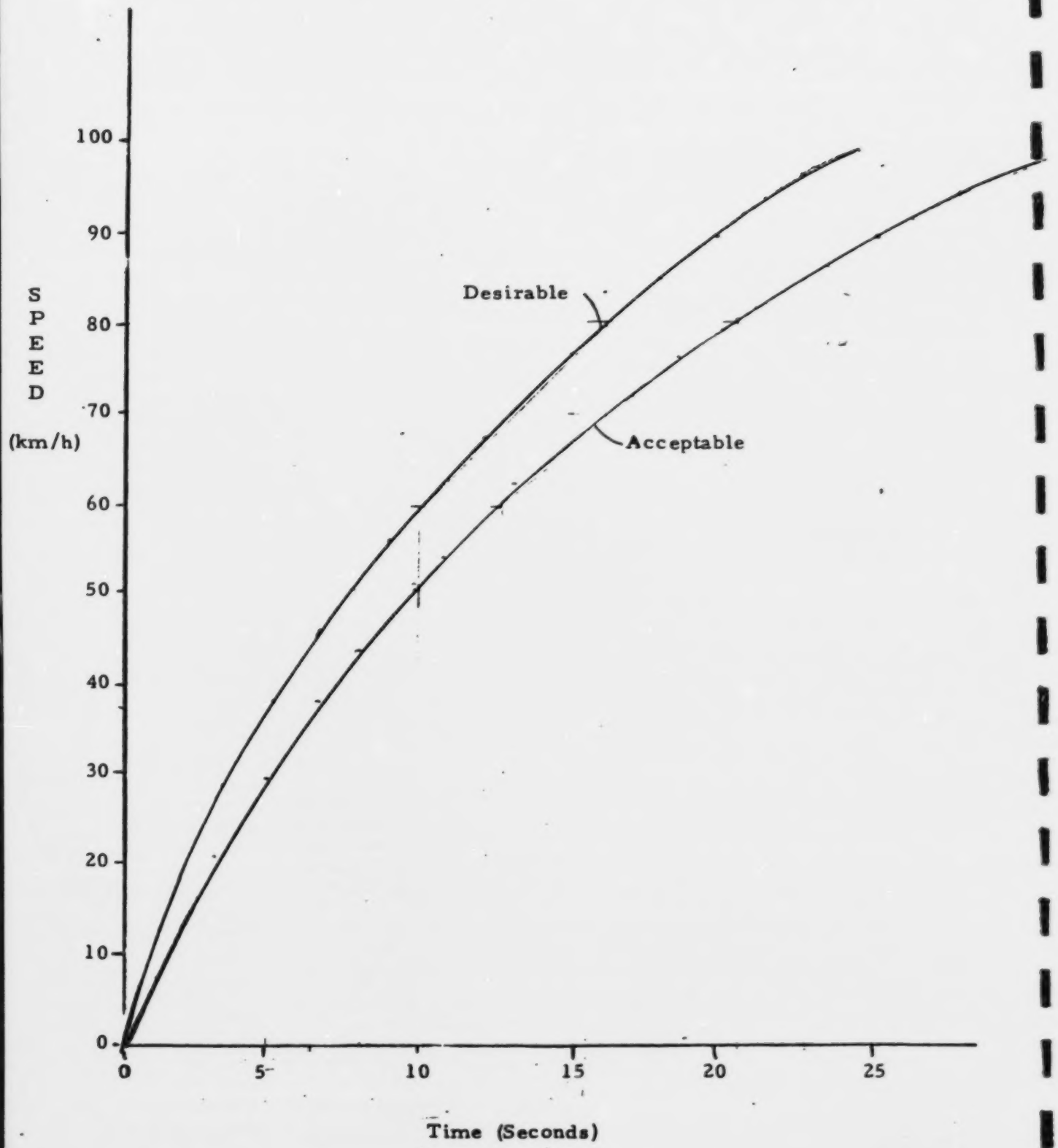
Design Speed (km/h)	50	60	70	80	90	100	110	120	130	140
Minimum Passing Sight Distance (m)	340	420	480	560	620	680	740	800	860	920
Crest to Rounded (m)	125	190	245	335	410	495	585	685	790	905

Note: Height of drivers eye 1.05 m.
Height of opposing vehicle 1.30 m.

It is essential that the hybrid vehicle should be able to overtake a vehicle travelling at 60 km/h on a highway designed for 80 km/h and desirable that it should be capable of overtaking a vehicle travelling at 80 km/h on a highway designed for 100 km/h. To meet these requirements the vehicle must accelerate from 60 to 90 km/h in not more than 12.5 seconds and desirably in 10 seconds. At the lower end of the scale for reasonable urban performance the vehicle should be capable of accelerating from 0 - 50 km/h in not more than 12.5 seconds and desirably in 8 seconds. Figure 3.1 shows typical time-velocity curves for vehicles meeting the criteria established above.

The vehicle must provide its maximum power output to achieve the acceleration required. In the case of the hybrid vehicle this requires that both the electric motor and heat engine operate on demand during periods of peak acceleration. The state of charge of the batteries may, therefore, limit the acceleration which can be achieved. It is intended that the batteries will be maintained above a specified minimum state of charge by using excess power from the heat engine to recharge as necessary. It should be possible to size the power train components to meet the acceleration requirement at an economically viable minimum battery state of charge. This factor will be investigated as the design study progresses.

Figure 3.2



Typical Acceleration - Specification Levels

3.3.3 Energy Consumption

The hybrid electric vehicle uses both fossil fuel in the form of liquid or gaseous hydrocarbons and electrical energy from the utility supply. The vehicle power train must be designed to provide optimum economy in the use of both energy sources while substituting electrical energy for fossil fuel energy to the maximum practicable extent. The proportion of fossil energy to electrical energy used by the vehicle at any instant increases as the distance travelled increases until, at the point which the batteries reach their minimum level of charge, all the energy required is drawn from the fossil fuel. The use of fossil energy will depend on the operating conditions, the battery capacity and the range of the vehicle between battery recharging.

The criteria selected for the specification require a very good fossil fuel economy up to a 120 km range operating on the EPA urban cycle. (See Appendix E.) In the interests of simplicity gasoline has been selected as the fossil fuel for the specification.

Under highway conditions the vehicle will operate on heat engine power with negligible use of the electric source.

3.4 Preliminary Performance

The specifications set out in this section are based on compliance with safety standards and on performance characteristics and energy consumption rates considered by the contractor to be attainable. During the course of the study, these and other hypothesis were reviewed with the Transportation Development Centre and were compared to "targets" used in the U.S. Department of Energy hybrid vehicle studies and others.

3.4.1 Basic Objective of Vehicle

To provide a cost effective low fossil fuel consumption means of urban and suburban transport for personnel and/or low density loads in commercial operations.

3.4.2 Intended Use

To transport designated payloads or passengers in urban traffic, with occasional periods of high speed cruise on suburban roads.

Typical missions would include:

I "Service" vehicles (operator plus materials)
- Bell Canada
- Hydro
- Domestic Appliance Servicing
- Municipal Services
- Security Patrols (public and private)
- Industrial Site Services including airports

II Light delivery vehicles (operator plus light cargo)
- Postal Service
- Parcel Delivery Services
- Food and Catering Services

III Commercial passenger vehicles (operator plus passengers and baggage)
Intracity Personnel Carriers
- Airport Conveyance
- Industrial Complex Conveyance

3.4.3 Basic Configuration

A two-door body and rear hatchback, mounted on a two-axle chassis. The body will be of utilitarian design and the interior will be readily convertible between passenger and cargo payloads.

3.4.4 Payload Characterisitics

	Acceptable	Desirable
(a) Payload (incl. driver)	350 kg	500 kg
(b) Max. seating cap. (incl. driver)	4 persons	4 persons
(c) Total cargo volume	$1.4m^3$	$2.0m^3$
(d) Entrance/Egress	Two side doors & hatchback	

3.4.5 Vehicle Weights and Dimensions

	Acceptable	Desirable
Wheelbase	270 cm	250 cm
Length	450 cm	350 cm
Width	165 cm	150 cm
Height	165 cm	150 cm
Curb Weight	1500 kg	1300 kg
Turning Circle (wall-to-wall)	11 meters	10 meters

3.4.6 Propulsion System Characteristics

- HYBRID, utilizing two prime movers;
  (a) heat engine
  (b) electric motor

- PRIMARY ENERGY STORAGE
  (a) fossil fuel (liquid or gaseous) for heat engine
  (b) lead acid battery pack for the electric motor

- SECONDARY ENERGY STORAGE
  (if regenerative braking is used)
  lead acid battery pack

- BATTERY CHARGING
  - utility power (off board charger)
  - motor/generator power

3.4.7 Vehicle Performance

	Acceptable	Desirable
Minimum non-refuelable range (km)	200	250
Cruise speed (km/h) (H.E. only)	85	95
Maximum speed (km/h) (H.E. only)	95	105
Acceleration (H.E. plus E.M.) Batteries at 25% charge or better		
0 to 50 km/h (secs)	10	8
0 to 90 km/h (secs)	25	20
60 to 90 km/h (secs)	12.5	10
Gradeability		
at 50 km/h	5%	7%
maximum	20%	25%

Energy Consumption - EPA Urban Cycle

Distance	40 km		80 km		120 km	
	Accept.	Desire.	Accept.	Desire.	Accept.	Desire.
Gasoline -						
consum. (l/100 km)	3.5	2.9	4.7	3.9	6.4	5.3
qty. consum. (l)	1.4	1.16	3.76	3.12	7.68	6.36
PLUS						
Electricity -						
consum. (kwh/100 km)	20.0	12.5	12.5	10.0	9.3	7.5
qty. consum. (kwh)	8.0	5.0	10.0	8.0	11.0	9.0

Energy Consumption - Highway
Gasoline only (l/100 km) Accept. 7.35, Desire. 6.13

3.4.8 Safety Standards

The vehicle must comply with the Canadian Motor Vehicle Safety Standards for "multi-purpose passenger vehicles".

4.0 CANDIDATE DRIVE TRAIN CONFIGURATIONS

Four candidate drive train configurations, potentially suitable for use in an advanced hybrid vehicle, were established and are examined in the section.

4.1 Advanced Parallel Hybrid - Figure 4-1

4.1.1 Background

This configuration is one wherein a heat engine and/or an electric motor may be used to drive the wheels independently or in combination.

The Marathon C-360 parallel hybrid (see Report #TP3765E) is representative of this type of vehicle in its simplest form, basically an electric vehicle converted to a hybrid by the addition of a heat engine which drives the electric motor through a centrifugal clutch.

The other end of the spectrum is the General Electric near-term hybrid experimental vehicle, a high performance passenger car with all of the conventional accessories and amenities, plus a microprocessor-based control system.

4.1.2 Characterization

The advanced hybrid vehicle as defined herein includes;

- a power-to weight ratio consistent with its intended missions, in the range of 0.16 to 0.20 hp/lb
- a heat engine designed for automotive use
- a D.C. motor, separately wound and suitable for regenerative braking
- a traction motor controller
- a transmission, either manual or automatic
- a system of clutches which will permit the following operations:
  - electric drive only
  - heat engine drive only
  - combined drive
  - regenerative braking
  - battery charging by the heat engine with the vehicle at a standstill
- a control system to optimize vehicle performance including fuel economy
- a "wall plug" battery charger which may be on-board or off-board

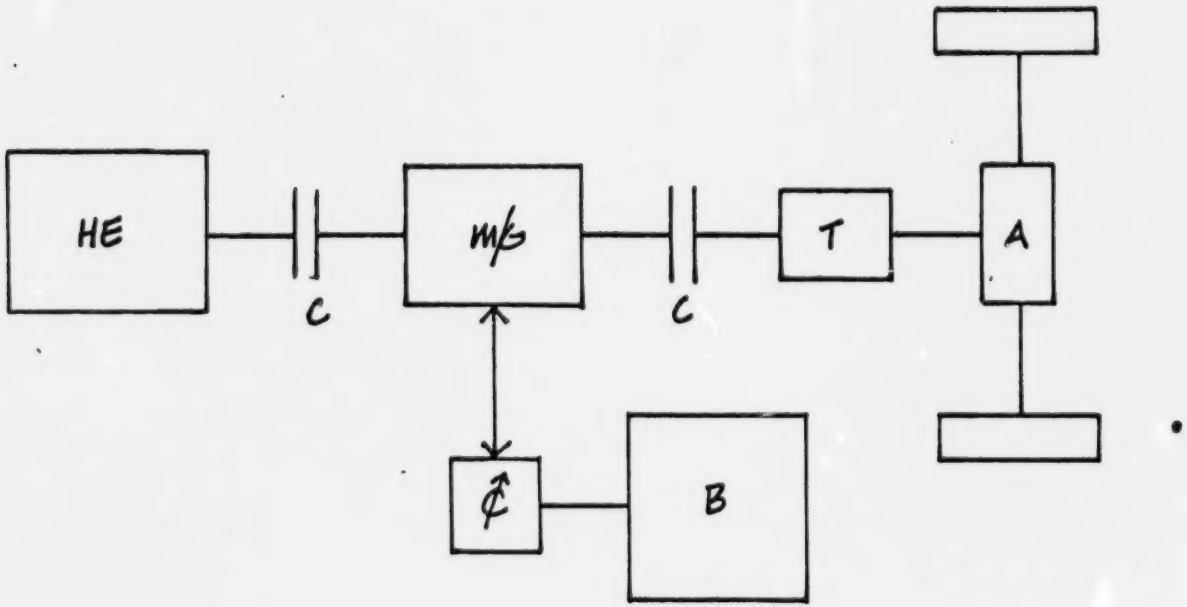


Figure 4.1 - Single Shaft Rear Drive Parallel Hybrid

4.1.3 Control Strategy

When operating in urban conditions during the summer the vehicle will be propelled by the electric motor alone up to certain power level demands at which point the heat engine will assume the load. The point at which the changeover takes place will vary with the state of charge of the batteries. For highway or suburban operation the heat engine will be the primary source of power. In both urban and suburban operation both power sources will be used to meet peak power demands.

During winter operation it will be necessary to operate the internal combustion engine continuously to provide adequate heating and defrosting capability. Under these conditions, the changeover from electric motor to heat engine power will take place at a much lower level and the hybrid vehicle will operate largely as a somewhat underpowered heat engined vehicle: the electric motor will still be used for load levelling. It will be necessary, for best fuel economy to achieve a balance between the time which the heat engine spends idling and the time it spends providing power. As the engine is relatively small for the task it will operate at a fairly high power fraction under most conditions and with careful selection of transmission shift logic good fuel economy will be achieved.

The basic philosophy is to achieve maximum fossil fuel efficiency by substituting "wall-plug" electricity whenever possible, in terms of battery state-of-charge and load demand.

4.2 Parallel Hybrid with Power Blending Differential - Figure 4.2

4.2.1 Background

This configuration is a conventional parallel hybrid except that the electric motor and heat engine inputs are combined in a differential transmission in order to better match their diverse speed-torque characteristics. This device has been considered previously by General Electric in their near-term hybrid vehicle. A variant proposed by the Ontario Research Foundation (see Appendix A) uses the motor as a generator to provide a variable speed transmission when the vehicle is operated in the heat engine mode.

The addition of the differential to the drive train permits the following operating modes:

- all electric drive with single fixed drive ratio
- heat engine drive with a single fixed ratio, or in the case of the ORF variant, with an infinitely

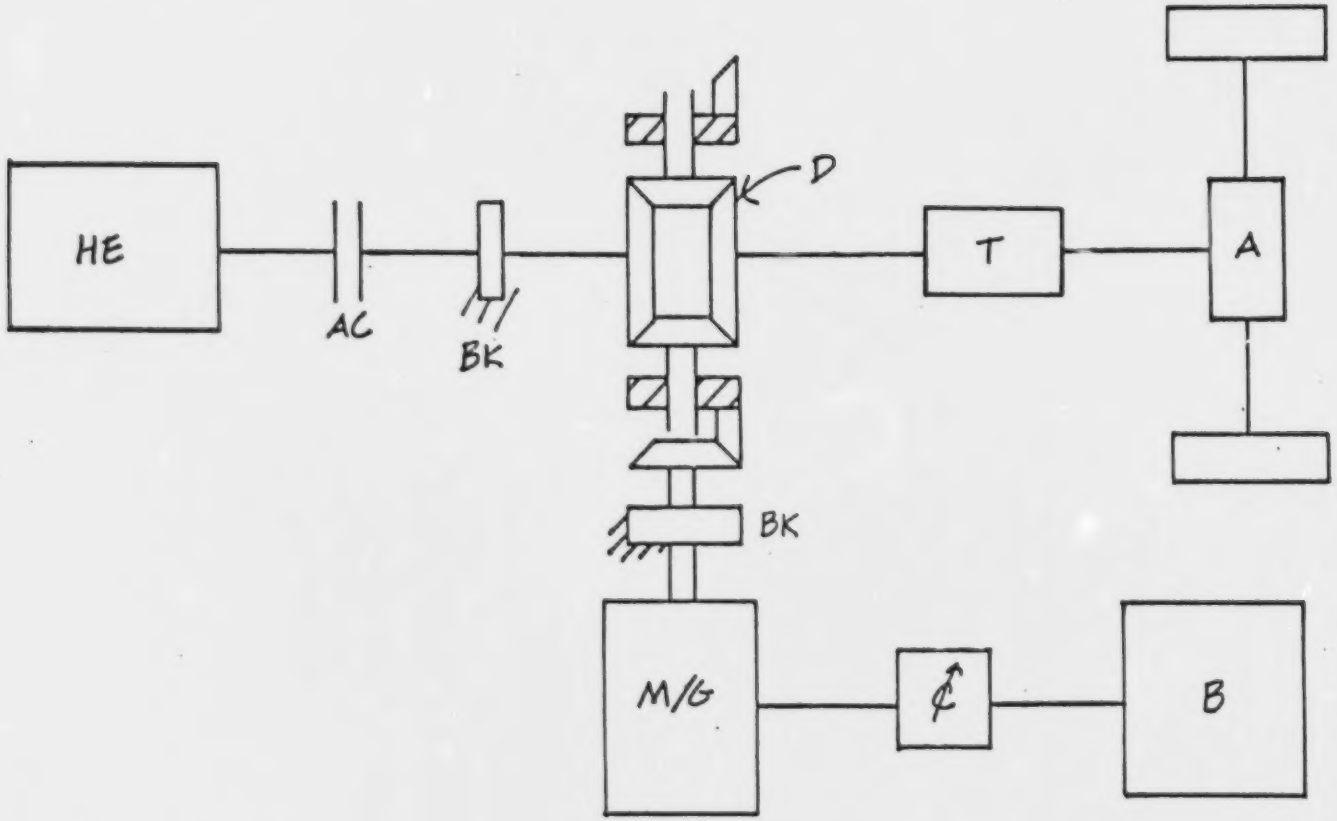


FIG 4.2 PARALLEL HYBRID WITH POWER BLENDING DIFFERENTIAL AND OPTIONAL REGENERATION

variable drive line speed ratio, modulated by the conversion of shaft horsepower into electric energy for battery charging.

- combined heat engine and electric drive with a fixed ratio for each power source.

4.2.2 Characterization

The drive line is characterized by:

- a power-to-weight ratio in the range of a 0.16 to 0.20 hp/lb.
- an internal combustion heat engine designed for automotive use
- a set of storage batteries
- a DC motor, separtely wound, and suitable for regenerative braking or power regeneration (ORF)
- a traction motor controller
- a clutch/brake assembly on the heat engine shaft and a brake on the generator/motor shaft in order to achieve the following modes of operation:
  - electric drive only
  - heat engine drive only
  - combined drive
  - combined drive with power regeneration (ORF)
  - regenerative braking
  - battery charging by the heat engine with the vehicle at a standstill
- a control system to optimize vehicle performance, including fuel economy
- a "wall-plug" battery charger which may be on-board or off-board

4.2.3 Control Strategy

The proposed control strategy in the case of the basic power blending differential is identical with that of the advance parallel hybrid defined in Section 2.1 herein.

In the case of the ORF variant an additional control feature will be required to regulate the output of the motor/generator so that the heat engine operates at its most economical point to meet the power demand.

4.3 Series Hybrid -Figure 4.3

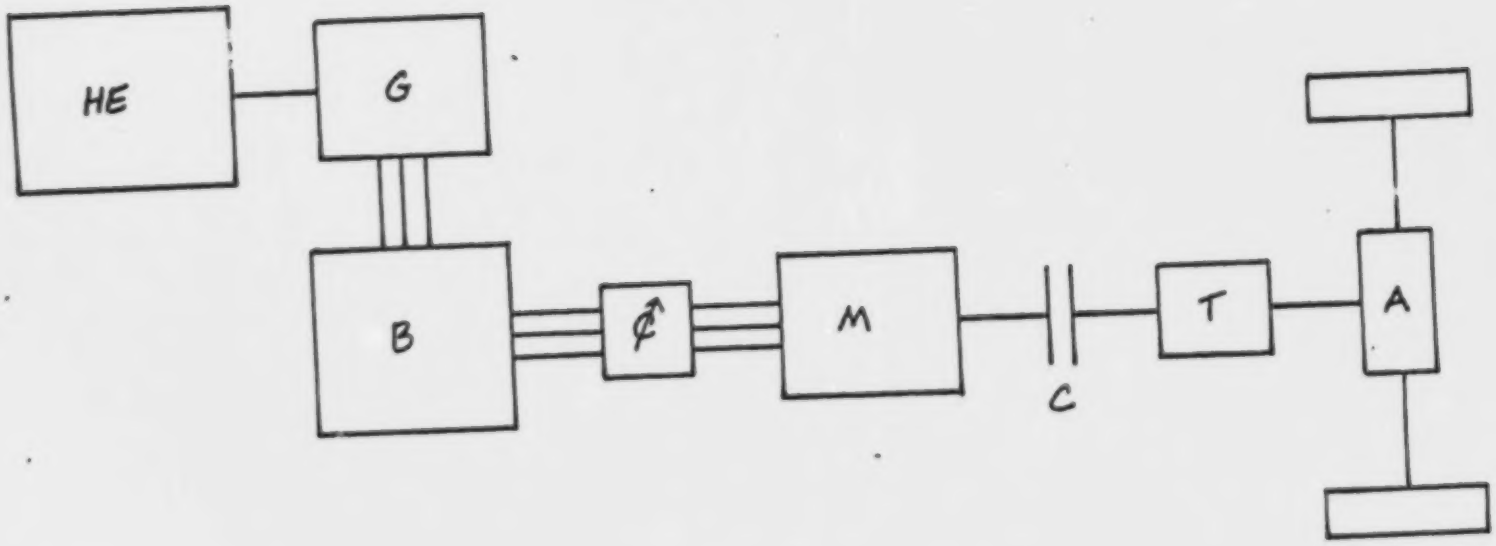


Figure 4.3 - Rear Drive Series Hybrid

4.3.1 Background

This configuration is one wherein the heat engine drives a generator which provides current to the traction motor. A set of batteries is floated across the output of the generator. The series configuration may be of either the "load levelling" design in which the heat engine comes into operation only when required to meet peak power demands or when the state of charge of the batteries falls to a predetermined level. In the latter case of operation will be generally similar to the parallel hybrid up to the point when full time operation of the heat engine is required. When the engine is operating full time, in either case:

- during periods of low demand by the traction motor controller, current is used to charge the batteries
- during periods of high demand by the traction motor controller (above the current levels which can be supplied by the generator) the batteries supply current up to the controller limit.

The intent of the load levelling configuration is not to substitute 'wall-plug" electricity for fossil fuel, but rather, to operate a heat engine sized for the average requirement at or near its maximum fuel efficiency and provide load leevelling with a modest battery pack.

The nominal series configuration seeks to substitue "wall-plug" electricity for fossil fuel over the first part of its range and to achieve the same economy as the load levelling design when the available energy stored in the batteries has been used.

4.3.2 Characterization

The series hybrid vehicles as defined herein include:

- a power-to-weight ratio consistent with its intended missions, in the range of 0.010 to 0.015 hp/lb.
- a heat engine, fitted with a variable speed governor
- a DC separately wound generator fitted with a voltage regulator system
- a DC traction motor, separately wound and suitable for regenerative braking
- a traction motor controller
- a set of storage batteries

- a control system to optimize vehicle performance including fuel economy

- the "wall-plug" battery charger may be on-board or off-board

4.3.3 Control Strategy

Due to the nature of the "load levelling" series design, with a modest battery pack, the vehicle is intended for normal operation with the heat engine running at governed speed. Load demands within the capability of the generator do not require any current to be supplied from the batteries, and permit charging of the batteries at low demand levels. As the load demand increases and exceeds the output of the generator, additional current is supplied by the storage batteries, up to the limiting current of the traction motor controller. Passenger compartment and defroster heat are available from rejected heat of the heat engine which is operating continuously.

The basic philosophy of the "load levelling" design is to maximize the fuel economy of the undersized heat engine by operating it at its most efficient point, and load levelling using a set of storage batteries of modest size. The batteries are sized on the power requirements imposed by load levelling rather than the energy storage requirements associated with the substitution of "wall-plug" electricity for fossil fuels.

The control strategy for the "nominal" series operates on the same control strategy as the load levelling design maintaining the batteries at a state of charge sufficient only to meet load levelling requirements. In winter the "nominal series" vehicle will use the same ocntrol strategy as the load levelling design.

4.4 Series-Parallel Hybrid - Figures 4.4 and 4.5

4.4.1 Background

This configuration combines certain of the characteristics of the preceding arrangements. Two variants of the series/parallel arrangement will be considered:

Type I - This arrangement is based on the use of an epicyclic gear train, such as a common differential, to divide and combine heat engine, motor and generator torques so that the heat engine always operates at its most efficient point. The differential acts as a continuously variable transmission by employing a power shunt technique.

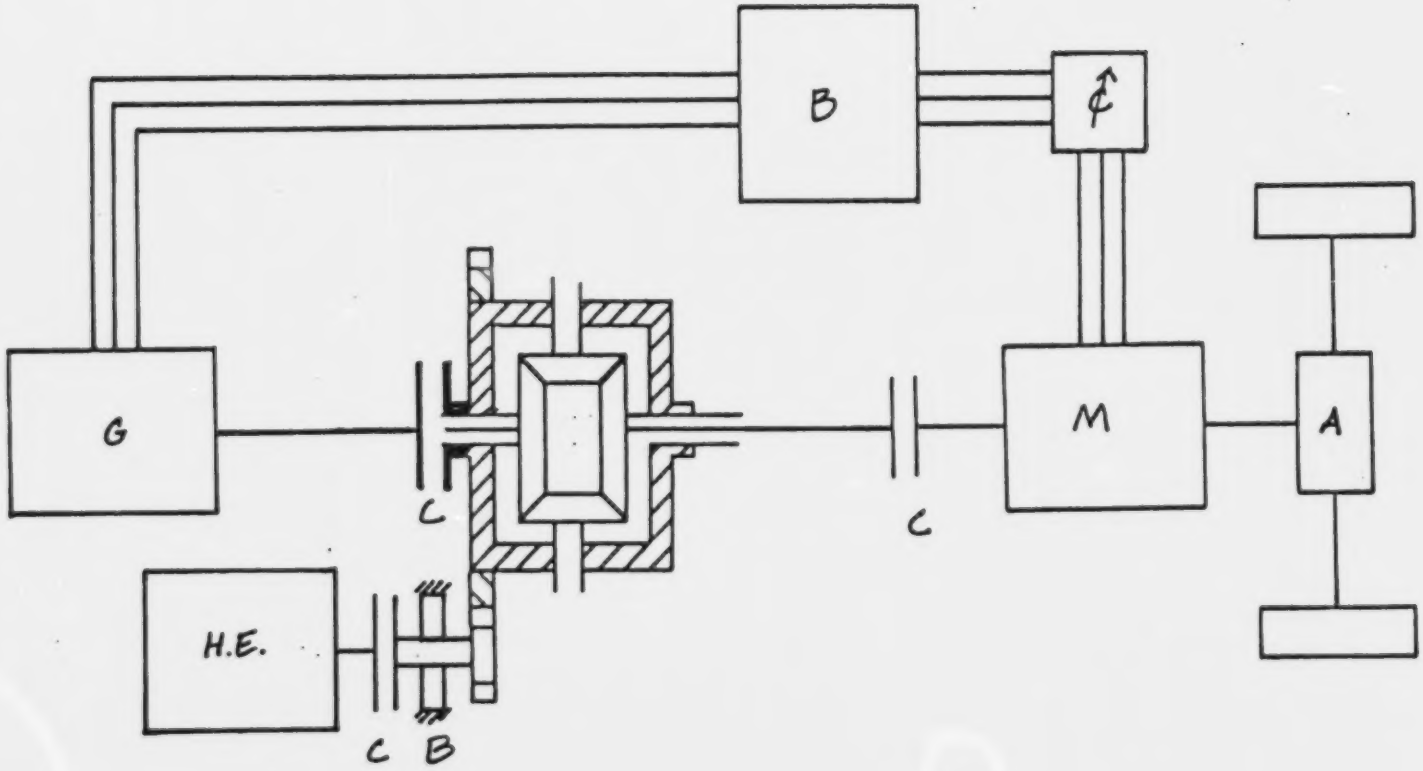


FIG. 4.4 SERIES / PARALLEL, REAR DRIVE HYBRID WITH POWER SHUNT TRANSMISSION

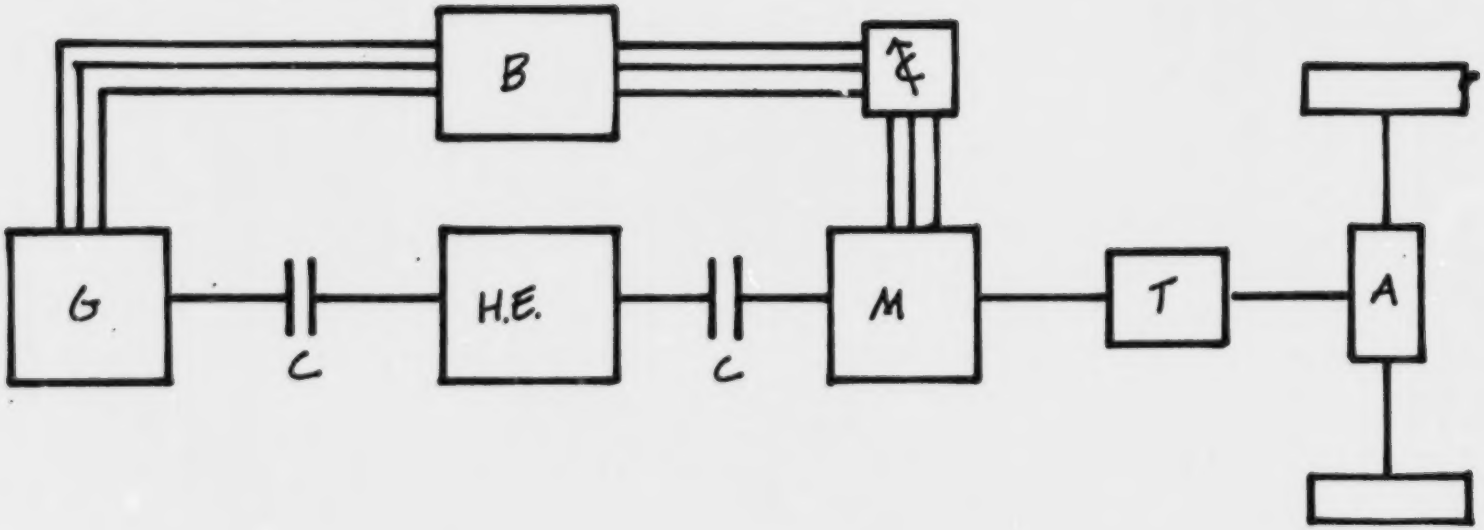


FIG 4.5 SINGLE SHAFT SERIES/PARALLEL HYBRID

Type II - This arrangement in its simplest form disposes the heat engine, electric motor and generator on the same centre line. It differs from the series hybrid only in the inclusion of a clutch which allows the heat engine to drive the vehicle through the elctric motor. The arrangement is intended to ensure that the heat engine operates at its most economical point for each power demand while eliminating as far as practicable, the electrical losses inherent in the series arrangement. It appears probable that a variable speed transmission will be required in the drive line to develop the full potential of the arrangement.

4.4.2 Operating Modes

The following operating modes are available:

Type I
- all electric drive with a single fixed ratio using the electric motor
- heat engine only with a single fixed ratio for medium speed operation
- combined electric and heat engine drive during start up and acceleration using the infinitely variable speed ratio provided by the differential with a power shunt provided by the generator and motor. The batteries may be used to supplement the generator.
- combined electric and heat engine drive during high speed operation

Type II
- all electric drive through the transmission using the electric motor
- heat engine only through the transmission
- combined electric and heat engine drive using the series mode during start up and low speed acceleration
- combined electric and heat engine drive during high speed operation and acceleration using the parallel mode

4.4.3 Characterization

The series-parallel hybrid vehicle is characterized by:

- a power-to-weight ratio in the range of 0.016 to 0.020 hp/lb
- a heat engine fitted with a variable speed governor
- a DC generator separately wound with voltage regulation
- a DC traction motor
- for Type I, a differential gear, an automatic clutch and a brake on the heat engine drive shaft and a lock up clutch on the differential shaft, or
- for Type II, clutches between the heat engine and the generator and the heat engine and the electric motor and a variable speed transmission to provide the following modes of operation in each case:
  - electric drive only
  - heat engine drive only
  - combined drive
  - regenerative braking
  - battery charging by the heat engine with the vehicle at a standstill
- a control system to optimize vehicle performance, particularly fuel consumption

4.4.4 Control Strategy

Type I

During highway and suburban driving when the heat engine is in use its speed will be controlled at the most economical level to meet the power demand by automatic variation of both the torque demanded by the generator and the torque supplied by the traction motor. The batteries will float across the generator output during this operation. After differential lock up occurs, power will be supplied by the heat engine and, when necessary, the electric motor to meet peak power demands.

In urban conditions the vehicle will operate in the all electric mode using the electric motor up to certain power demand and battery charge levels beyond which the heat engine will cut in to provide load levelling.

Type II

During highway and suburban driving the heat engine will be used as the primary power source and will drive the vehicle through the variable speed transmission which will

ensure that, within reasonable limits, the engine operates at an economical point. The electric motor will be used to meet power demand in excess of that which can be provided by the heat engine.

In urban conditions the vehicle will operate in the all electric mode or in the series mode depending on power demand and battery state of charge.

A change in control strategy similar to that applied to the Advanced Parallel Hybrid will be required for both types during urban operation under winter conditions.

The philosophy is to achieve maximum fuel economy from the heat engine by operating it only within its most economical range and also to substitute "wall-plug" electricity for fossil fuel wherever practicable.

4.5 Comparison of Candidate Configurations

4.5.1 Preliminary Approach

The aim of the program is to provide a cost effective, low fossil fuel consumption means of transportation. The four power train configurations which have been proposed use different techniques to achieve this aim and it is apparent from a preliminary appraisal that the more complex systems have obvious disabling shortcomings.

The power differential and the ORF proposal are variants on the parallel system, each providing the ability to blend the power from the heat engine and the electric motor in a torque summing differential so that each source provides a fixed proportion of the total. Approximately the same result may be obtained by introducing a fixed gear ratio between the two sources and designing the control system to proportion the load. While this arrangement will lack the smoothness of the differential system during the changeover from one source to the other it provides a far simpler and less costly system.

The control strategy used with the Type I series/parallel configuraton starts and operates the vehicle using the electric motor up to a pre-determined speed (V Mod) at which point the heat engine is activated. The differential and the generator-electric motor combination then serve as a continuously variable transmission to ensure that the heat engine always operates at its most fuel efficient point. While this sytem appears to offer potential for efficient operation, particularly in cold winter conditions, this has never been realized and a very similar system built about 1970 gave only 50% overall efficiency on dynamometer testing with projected improvement to 75% after development (Reference 4.1).

There are alternative and more efficient ways of providing a continuously variable transmission which could be used with the parallel configuration to provide a simpler, less costly power tran configuraton than the Type I series/parallel proposal.

The Type II series/parallel configuration also seeks to maintain heat engine operation at an economical load point by using either series or parallel operation or both simultaneously to provide a form of load levelling for the engine. The system will provide enhanced operating efficiency only if the electrical losses during series operation do not exceed these arising from transmission losses and transmission/engine matching in the parallel configuration. There is evidence (Reference 4.3) that very good transmission matching and shift logic can be obtained using the type of control system envisaged for the parallel configuration and that there is nothing to be gained by going to the additional cost and complexity of the Type II series/parallel arrangement. The more conventional series and parallel configurations which form the basis of the systems discussed above are capable of reasonable efficiencies without the drawbacks associated with the more complex systems and will be evaluated in detail.

4.5.2 Advanced Parallel and Series Configurations

For the purpose of comparative evaluation concepts for parallel and series vehicles potentially capable of meeting the requirements of the performance specification were prepared. The concepts were based on a light pick-up van typical of those marketed by several manufacturers. The vehicle in its basic form has a curb weight in the region of 1160 kg with a payload of 450 - 650 kg.

It was found when preparing the concept for the series vehicle that, if a heat engine and generator sized to meet the average power requirement is employed, the battery is significantly larger than that originally envisaged with the series load demanded by the specification requirements. The "load levelling" and "basic" series configurations for the applications defined in the specification are, therefore, identical in design.

The leading characteristics of the concepts are set out below:

	Parallel	Series
Rolling Coefficient (CR)	0.12	0.12
Drag Coefficient (CD)	0.45	0.45
Gross Vehicle Weight (kg)	1820	1890

Engine (KW)	35	15
Motor - Peak Power (KW)	18	35
Batteries	10 x 6 volt	10 x 12 volt
Weight (kg)	295	363
Generator (KW)	NA	12
Transmission	4 speed auto shift	NA

4.5.3 Control Strategies

The control strategies for the concepts which were used in the evaluation are set out below.

4.5.3.1 Parallel Hybrid Control Strategy

1. Different strategy for hot and cold weather
   - hot weather - electric motor primary
   - cold weather - heat engine primary
2. Primary prime-mover supplies power when possible.
3. Second prime-mover used to meet peak power demand.
4. Heat engine always primary for long highway trips.
5. Engine used in on/off mode when the electric motor is primary.
6. Excess power from heat engine used to charge batteries when state-of-charge falls to a specified value (e.g. 25%)
7. Heat engine used more as battery state-of-charge decreases.
8. Limp-home mode on heat engine alone.
9. Microprocessor controls
   - engine clutch operation
   - initiation of battery charging
   - designation of primary prime mover
   - possibly power splitting between engine and motor and gear shifting

4.5.3.2 Series Hybrid Control Strategy

1. Batteries supply electrical energy if possible until SOC = .30.

2. If batteries can not meet electrical demand, then engine/generator turned on and batteries make up difference.

3. Engine always operates at 4000 rpm and fixed throttle (14 Kw output).

4. Engine runs continuously when battery SOC falls to 30% and continues to charge until SOC = 35%.

5. Excess generator output is used to charge batteries.

6. Generator field is controlled to match battery voltage.

4.5.4 Computer Simulaton Technique

4.5.4.1 HYVEC Program

The performance of the parallel and series vehicle concepts was compared using the Hybrid Vehicle Calculation (HYVEC) to simulate the operation of the vehicles.

The HYVEC program was developed by the General Electric Company to support the design of hybrid electric vehicles and has been shown to provide adequate simulation of hybrid power train operation as far as gasoline and electrical energy use and speed and acceleration are concerned. The HYVEC program is described in Appendix D.

4.5.4.2 Reference Vehicle

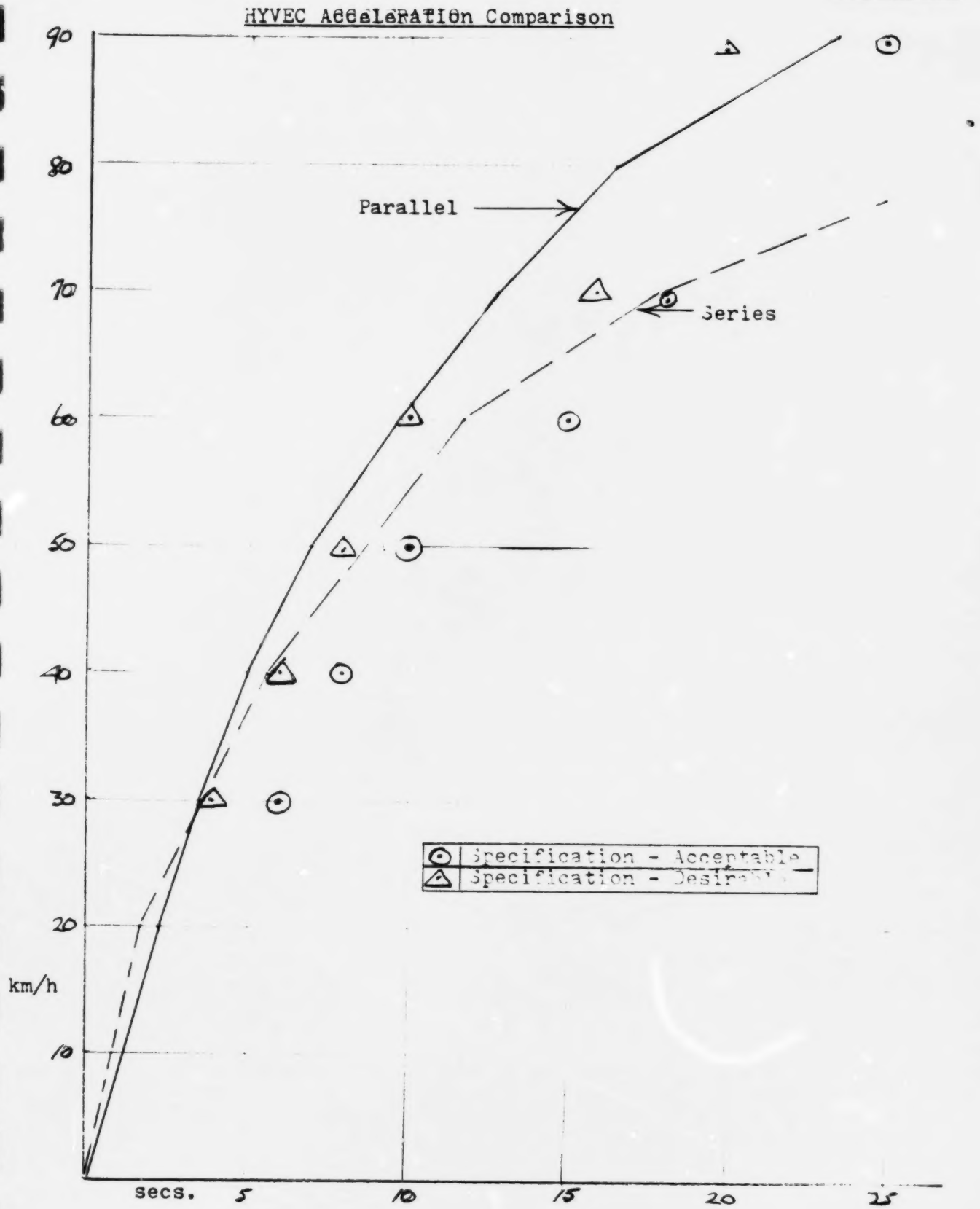
The HYVEC program requires a reference vehicle of conventional design to form a base line in the performance computations. Initially Datsun pick-up truck, reduced in length and with a cover over the box was selected as the reference vehicle for the evaluation. This vehicle had a weight of 1400 kg and was representative of the class of vehicle on which the concepts were based.

4.5.5 Road Performance

Both the series and the parallel concept vehicles have sufficient installed power to meet the desirable maximum speed requirement of 105 km/h. The parallel vehicle has the ability to sustain this speed indefinitely. The ability of the series vehicle to sustain speeds over 80 km/h is limited by battery capacity and its highway cruising speed is limited to about 75 km/h, well below the acceptable specification level of 85 km/h.

Figure 4.6 compares the acceleration of the oncepts with the requirements of the specifications. Both vehicles meet or exceed the desirable level at 0 - 50 km/hr and the

FIGURE 4.6


HYVEC Acceleration Comparison
90
80
70
60
50
40
30
20
10
km/h
Parallel
Series
Specification - Acceptable
Specification - Desirable
secs.
5
10
15
20
25

parallel concept attains this level for 0 - 90 km/hr. The series concept however fails to meet the acceptable level for 0 - 90 km/hr.

The parallel concept has the potential to meet the desirable level of 6 seconds for acceleration from 60 - 80 km/hr, the series concept achieves neither the desirable nor the acceptable level.

Figure 4.7 compares the acceleration performance of the series concept using both power sources with that when using the electric motor only.

4.5.6. Fuel and Energy Consumption

The fuel consumption of the two concepts during simulated operaton on the EPA urban driving cycle is shown in Figure 4.8. The acceptable and desirable specification levels are also shown.

The series comcept consumes little or no fuel when operating primarily on the electric motor and batteries out to a range of 35 km. At this point the heat engine is started and operated continuously at an economical governed speed to drive the generator and "float" the batteries while providing power for the motor. Excess generator power will maintain a satisfactory state of charge of the batteries. The fuel consumption remains relatively steady during this phase.

The parallel concept has an initially low fuel consumption which increases slowly as the battery charge decreases until it reaches a steady maximum at about 80 km range when excess engine power is used to recharge the batteries during the engine operating cycle.

The series vehicle meets the desirable fossil fuel consumption criteria at the 40 km point but exceeds the acceptable levels at 80 and 120 km. The fuel consumption of the parallel concept is very slightly in excess of the acceptable level at the 40 and 80 km points and significantly below it at 120 km.

The electrical energy consumed by each vehicle during the urban cycle is shown in terms of battery loss of charge in Figure 4.9.

As the series concept has only very limited highway capability no valid comparison can be drawn between the two concepts. The parallel concept will consume 6.3 litres per 100 km when operated on the EPA highway driving cycle: this may be compared with 7.8 litres per 100 km for the reference vehicle under the same conditions.

FIGURE 4.7

HYVEC Comparison Series Vehicle Acceleration
Electric Motor Only - Electric Motor and Heat Engine

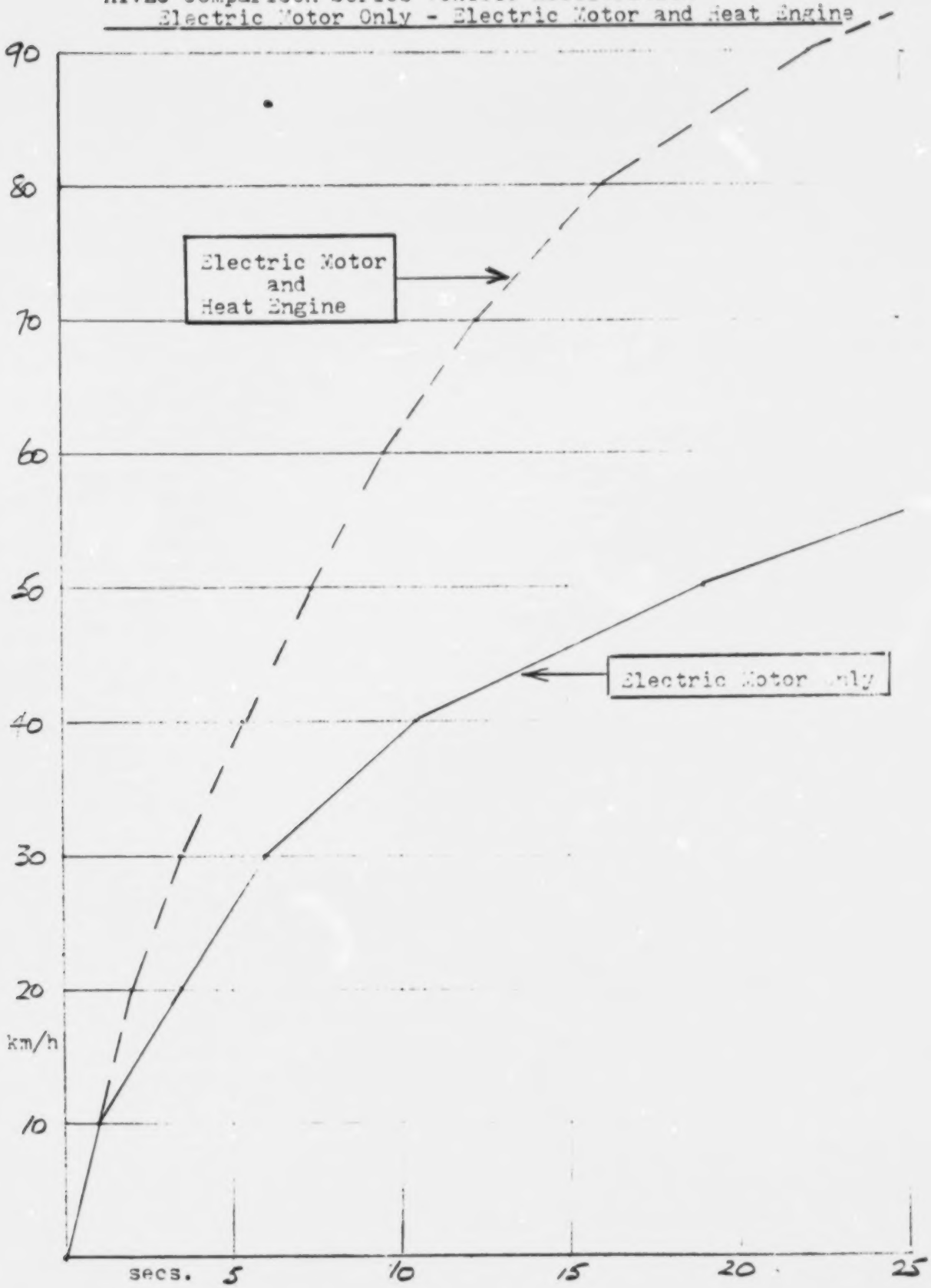


FIGURE 4.8

HYVEC Simulation - Fosil Fuel Consumption
EPA Urban Cycle - 20C

Series and Parallel

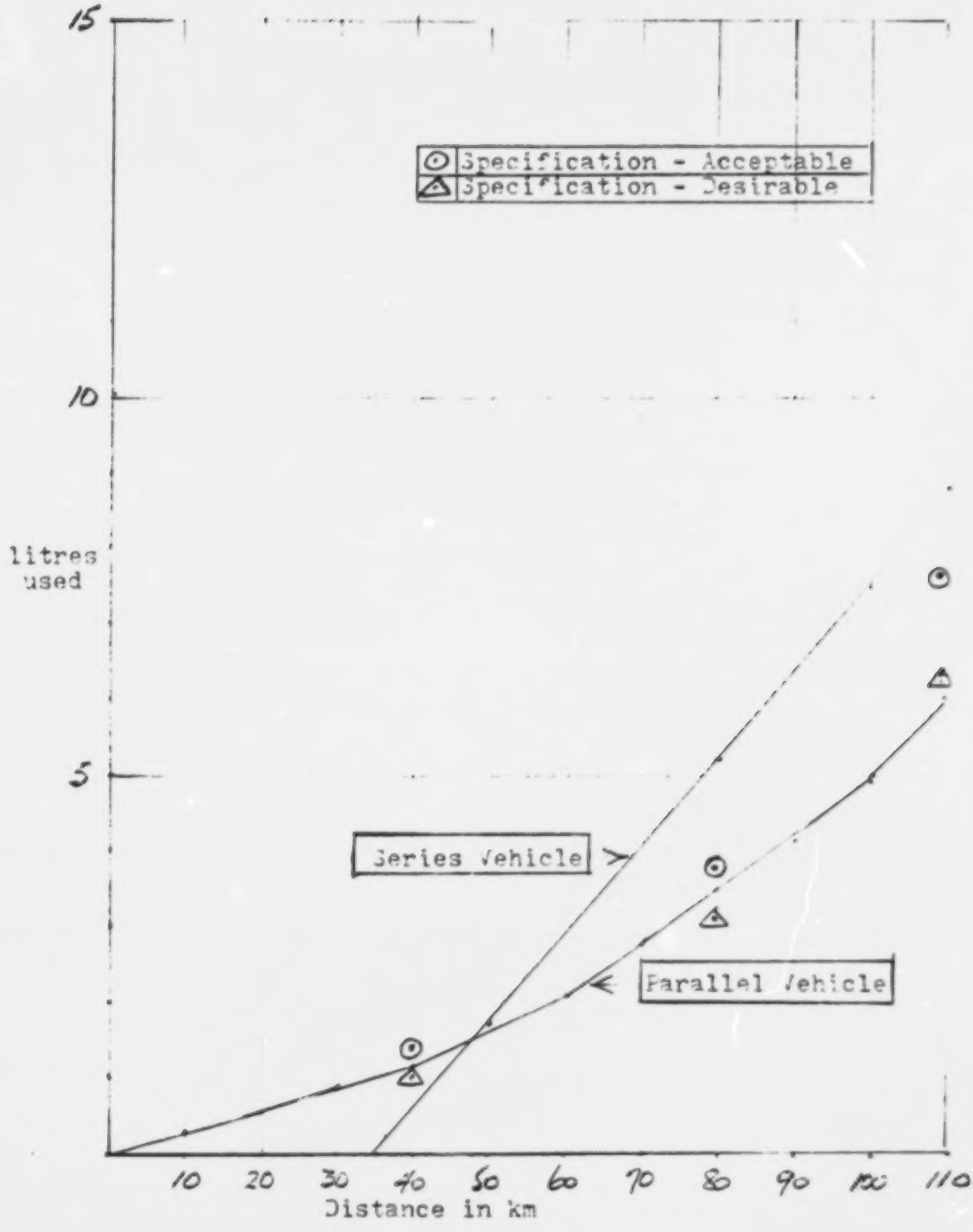
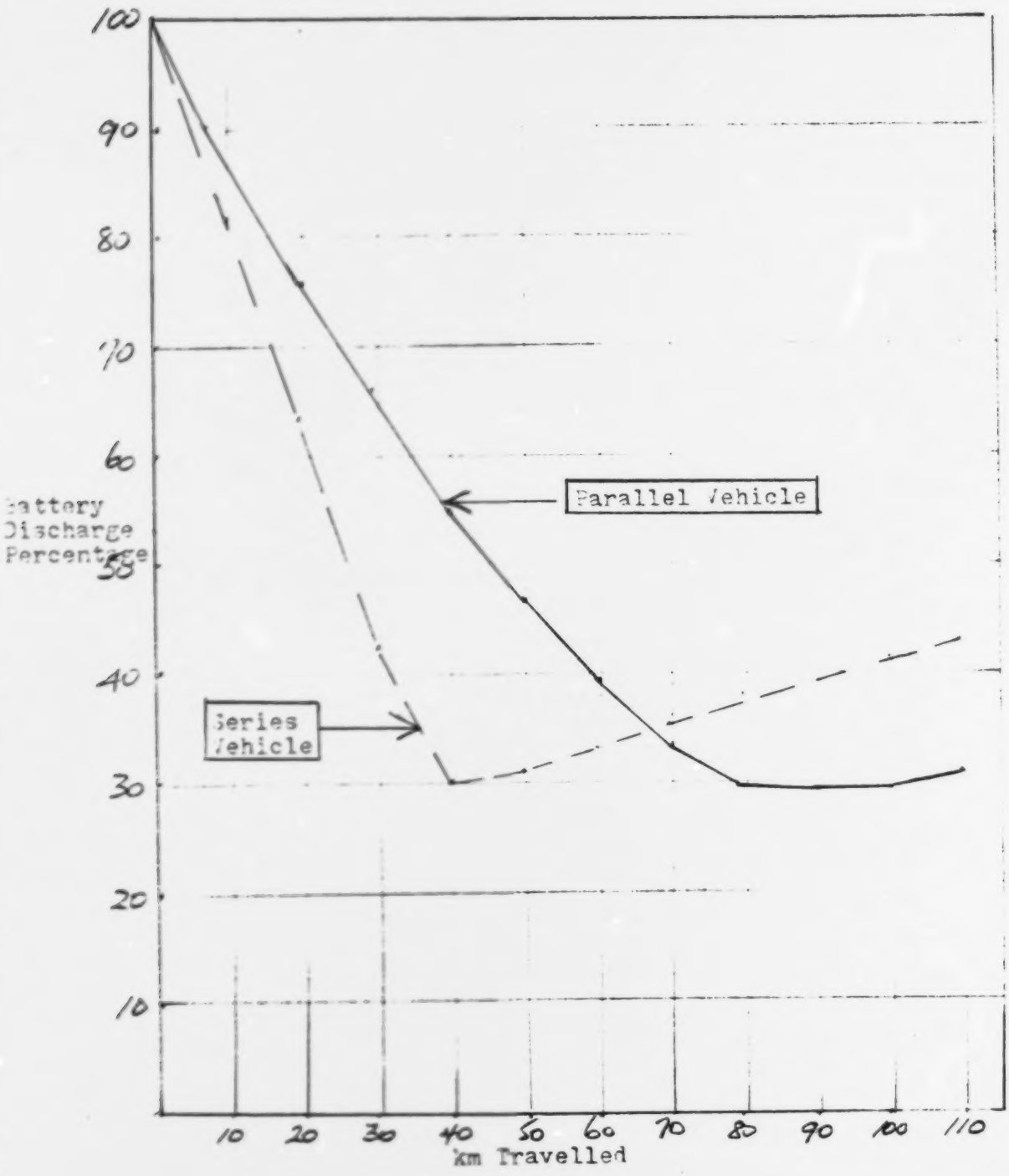


FIGURE 4.9

HYVEC Comparison - Electric Energy Consumed



4.5.7 Effect of Cold Weather

Canada experiences a severe winter and, in most parts, cab heating and windshield defrosting is required to a greater or less extent from 30th September to 1st May. Winter operation is discussed in some detail in paragraph 5.5 where it is concluded that, as far as possible, heat rejected by the heat engine should be used to heat the cab and passenger compartment. It is necessary to modify the control strategy of both series and parallel concepts for winter operation to provide for continuous or near continuous heat engine operation. In the case of the series vehicle this requires operation in the load levelling mode with the heat engine operating at a somewhat lower power fraction than previously and in the case of the parallel vehicle the heat engine takes over from the electric motor as the primary power source.

The fuel consumption of the vehicles operating on the modified strategies to provide sufficient heat for the cab in extreme (-30oC) winter conditions is shown in Figure 4.10 compared with the curves for the summer strategy.

The parallel concept clearly maintains its advantage under these conditions. With somewhat more sophisticated strategy which would provide intermittent operation of the heat engine at low vehicle speeds during less cold conditions the fuel consumption curve would lie between that for the extreme cold and that for the summer.

In figure 4.11 the comparison is extended to include the parallel vehicle using a fuel fired heater for cab heating and the reference vehicle.

4.5.8 Discussion

The simulations demonstrate that the series vehicle is clearly unsuitable for operation on suburban highways, it is unable to sustain highway speeds above 75 km/h and has insufficient acceleration to allow safe overtaking. This could be corrected by installing a larger heat engine and generator, possibly with increased battery capacity but the resulting vehicle with a 25 KW heat engine and 22 KW generator would be unreasonably heavy and the fuel consumption in urban driving conditions would be further increased by the necessity to operate the heat engine at a low power fraction.

The series vehicle has an advantage in fuel consumption in urban driving at low ranges when it operates primarily as an electric vehicle. At all other ranges the parallel concept is clearly superior.

The parallel vehicle meets or exceeds most of the important specification criteria and is capable of operating

Figure 4.10

Influence of Low Temperatures
on the Fuel Consumption of
Parallel and Series Hybrids

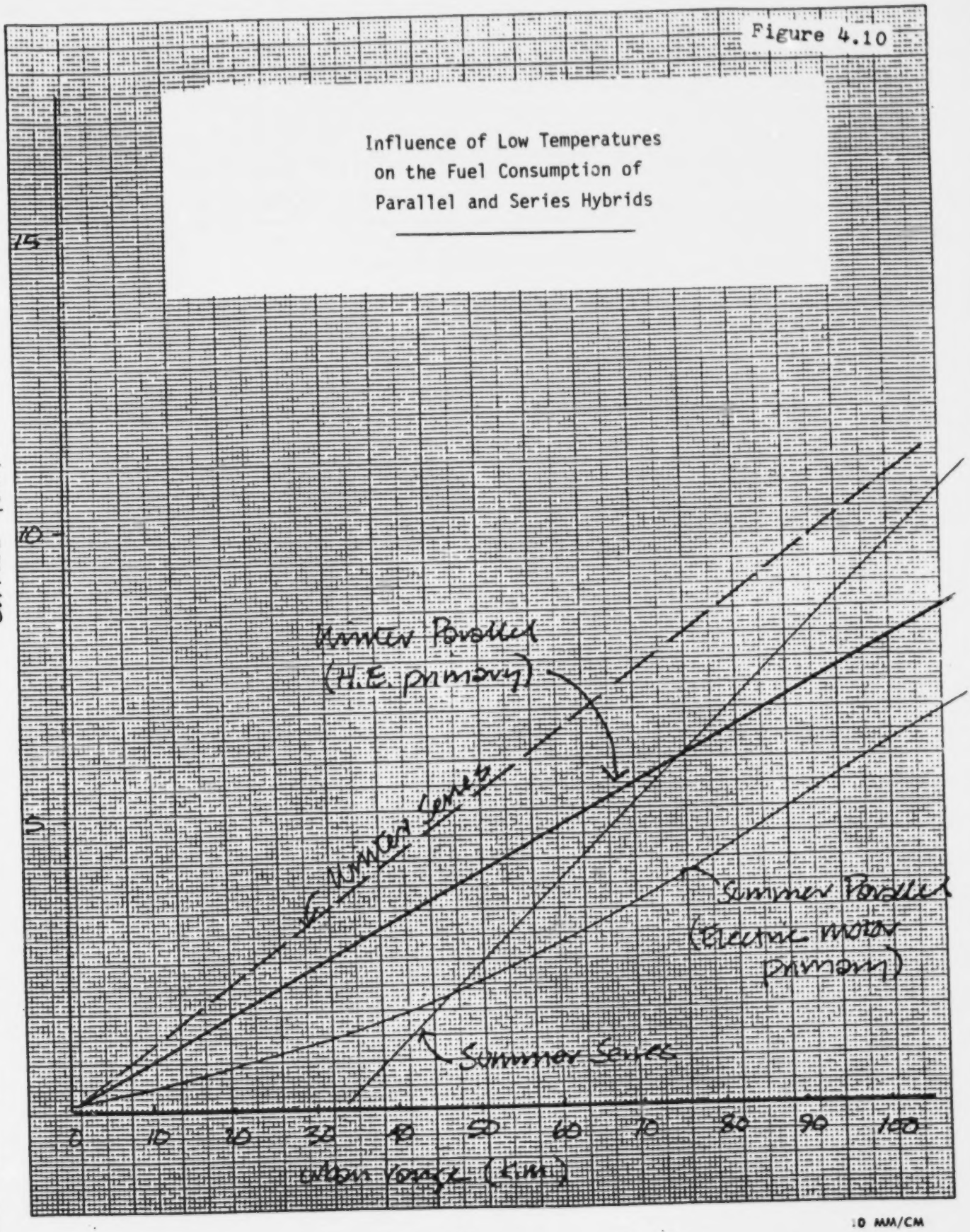
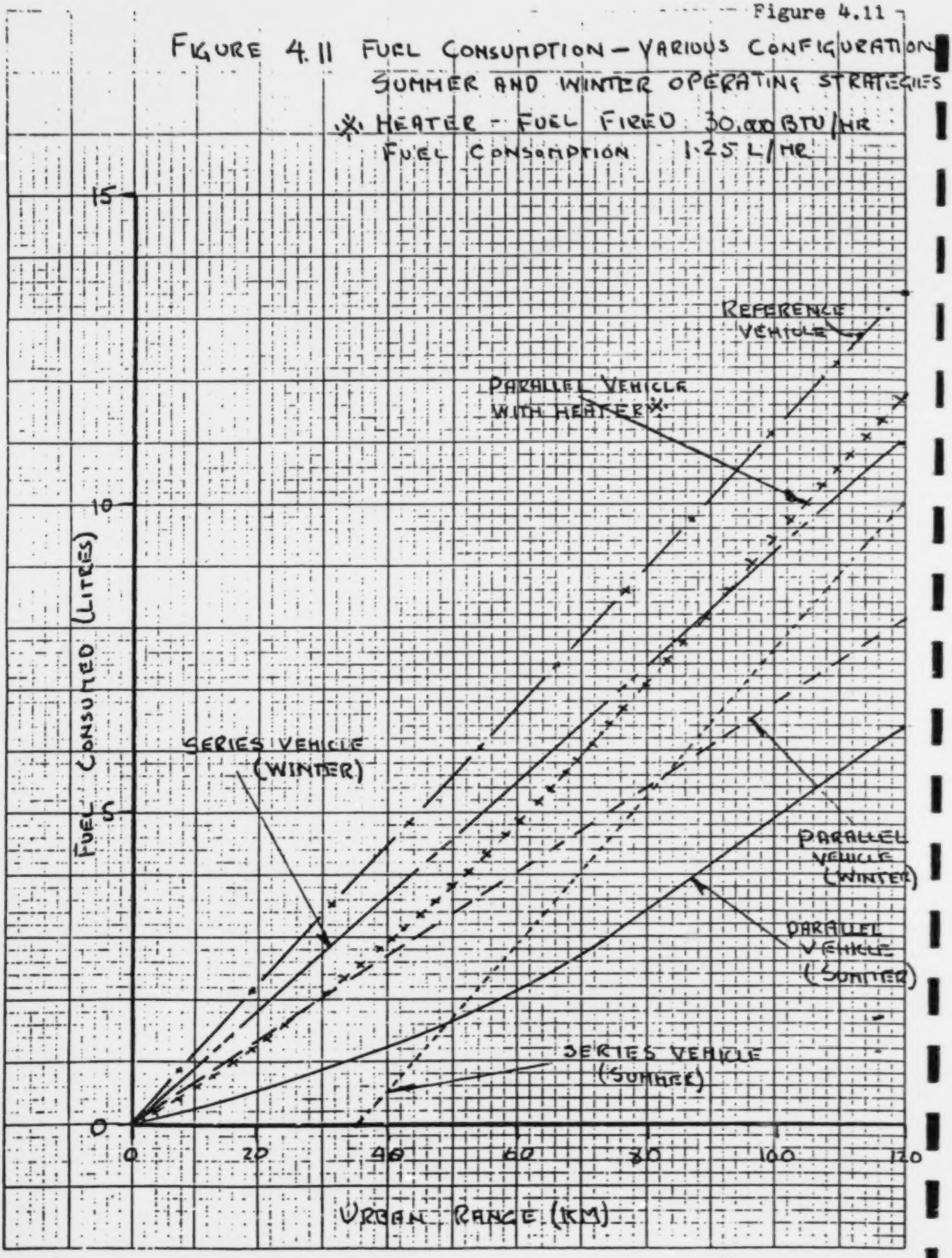


FIGURE 4.11 FUEL CONSUMPTION – VARIOUS CONFIGURATION SUMMER AND WINTER OPERATING STRATEGIES



economically in Canadian winter conditions: some very careful development will be required to ensure that this latter potential is fully realized.

The net production cost of the parallel hybrid is likely to be somewhat less than that of the series vehicle. The latter requires an additional electric generator and control equipment and a larger battery pack the costs of which will more than offset the savings occuring from the use of a smaller engine and elimination of the transmission. Maintenance costs for the parallel vehicle will also be less primarily because of the smaller battery pack.

4.5.9 Conclusions

It is concluded that:

- the acceleration of the parallel concept is significantly higher than that of a series concept of approximately the same weight and primary source rating
- the series concept is unsuitable for operation on suburban highways becuase of its low acceleration and low cruising speed
- the series concept uses more fossil fuel than the parallel vehicle at all ranges more than 50 km under urban conditions
- the parallel concept maintains its advantage over the series vehicle during low temeprature operation provided that the operation strategy provides rejected ingine heat for cab heating
- the parallel concept provides the best combination of characteristics for an advanced hybrid vehicle.

REFERENCES

4.1 SAE Paper 710235 - An Electromechanical Transmission for Hybrid Vehicle Power Trains - Design and Dynamometer Testing - G.H. Gelb et al

4.2 SAE Paper 820266 - The Hybrid Test Vehicle (HTV) - from Concept through Fabrication and Marketing - A. Burke

4.3 Near Term Hybrid Vehicle Program - Final Report General Electric Co. 1979

5. DEVELOPMENT OF DESIGN

5.1 Definition of Principal Vehicle Characteristics

It is necessary to make a preliminary estimate of the weight, power requirements and trasmission requirements to establish a basis for the identification of suitable components for the hybrid vehicle. In this process preliminary estimates of the size and weight of the equipment needed for the hybrid vehicle are required; these estimates are based on experience with similar vehicles and will be refined by the computer analyses conducted later in the study.

5.1.1 Weight Estimate

The following power train components will be required:

	Weight
- Engine, 0.8 - 1.0 L 35 - 45 HP with accessories and cooling system	75 kg
- Separately excited 12 HP DC motor, with clutch	66 kg
- 10 x 6 volt lead acid batteries at 27.2 kg each	272 kg
- Battery box and cables 53 cm x 91 cm	23 kg
- Controller and controls	45 kg
Total power train components	481 kg

The addition of the payload of 350 kg provides a total of 831 kg which must be added to the chassis of any vehicle which is to be converted to a hybrid electric propulsion system after removal of the existing engine and accessories. In the class of vehicle under consideration the engine which would be removed will probably not exceed 2.5 L capacity and will have a weight of about 159 kg with accessories and cooling system. The vehicle selected should, therefore, have a payload capacity of at least 831 - 159 kg = 672 lbs before conversion.

Either the Chrysler T115 van or the Datsun light pick up truck appear suitable candidates for conversion at this stage and would produce hybrid vehcles having very similar characteristics.

The projected weights for a hybrid based on the Chrysler T115 van are:

Original Curb Weight	1225 kg
Power Train Conversion and Payload	672 kg
Gross Vehicle Weight	1897 kg

This weight will be used to estimate power requirements and transmission characteristics.

5.1.2 Power Requirements

5.1.2.1 Vehicle Characteristics

Gross Vehicle Weight	1897 kg
Aerodynamic Drag Coefficient (C_D)	0.45
Overall Height	150.8 cm
Overall Width	164.3 cm
Frontal Area (A) - estimated	1.95 m^2
Tires P195-755R/14	
Revolutions per km	520
Rolling Resistance Coefficient (C_R)	0.012 + 0.00003V
Brake Drag Coefficient (C_R)	0-002

5.1.2.2 Operating Conditions

Smooth pavement

Ambient temperature 21°C

Average cross wind 16 km/h

5.1.2.3 Performance Requirements

	Acceptable	Desirable
Cruise Speed km/h (Heat Engine only)	85	95
Maximum Speed km/h (Heat Engine only)	95	105

	Acceptable	Desirable
Acceleration (Heat Engine plus Electric Motor)		
0 - 50 km/h (secs)	10	8
0 - 90 km/h (secs)	25	20
Gradeability		
Maximum	20%	25%
At 48 km/h	5%	7%

5.1.2.4 Motion Resistance

Aerodynamic Drag (FA) = $0.00249\ CD.A.V.^2$ lb
where V = speed in m.p.h.
The value of F_A will be increased by 10% by the cross wind.

Tire resistance (F_r) = $W(0.012 + 0.00003V)$ lb

Brake Drag (F_B) = $W.C_B$ lb

Gradient Resistance (Fa) = $W.\frac{G}{100}$ lb
where G = percentage grade

Total Motion Resistance (F) = $F_A + F_T + F_B + F_G$

5.1.2.5 Driveline Efficiency (E) (Direct Drive)

E = 0.99 (Transmission) x 0.90 (Hypoid Axle) x 0.99 (Drive shaft Axle Bearings) = 0.88

5.1.2.6 Power Required (HP)

$$HP = \frac{F.V}{375\ E} = \frac{FV}{330}$$

Speed (km/h) V	Gradient (%) G	Horsepower HP
85	0	22.6
95	0	28.6
105	0	35.9
48	5	29
48	7	31

5.1.3 Overall Transmission Ratios (R)

At maximum speed I.C. take engine speed as 4,500 rpm

For V max = 105 km/h, R = 4.95

For V max = 95 km/h, R = 4.5

For maximum grade (G)

Torque from I.C. engine (est. max. lb ft)	45
Torque from Motor (typical)	70
Total available torque	115 lb ft

Torque required to climb 25% grade - 1000 lb ft

Overall ratio at transmission efficiency of 84% = 10.5

The total range required in the transmission is approximately 2.3:1

5.1.4 Engine Power Requirements

The horsepower requirements developed above may be used as a guide in component selection. To ensure that the vehicle maintains its performance when the engine output is reduced 10% by wear and loss of tune the engine selected should be capable of developing about 40 HP at 4500 rpm. Such an engine may be expected to be rated at about 45 HP at its maximum speed of 5500 to 6000 rpm.

5.1.5 Commercially Available Components

A market survey revealed that there were 11 vehicles available on the Canadian market potentially suitable for conversion to hybrid vehicles following the procedure outlined above. These vehicles may be expected to provide a source of components and assemblies suitable for inclusion in a hybrid vehicle. The salient characteristics of the vehicles are shown in Table 5.1.5.

5.1.6 Summary

A hybrid vehicle developed from a conversion of the Chrysler T115 Van/Station Wagon would have a gross weight in the region of 1900 kg. An I.C. engine rated at 40 - 45 HP would allow the vehicle to maintain the desired maximum speed using the engine alone. The drive train should provide an overall ratio of 10.5 with a minimum transmission range of about 2.3:1. A number of other vehicles incorporating potentially suitable components are available on the Canadian market.

TABLE E-1.5

LEADING CHARACTERISTICS - 1983 LIGHT TRUCKS

Make and Designation	Origin	Drive F or R	WB (in)	L (in)	W (in)	H (in)	GVW (lb) Range	Rated Payload (lb) Regular	Engine Type	Engine HP	Transmission Type	Transmission Ratios	Tires	Fuel Consum. L/100
Chevrolet S10	US/Cda	R	108.3 117.9	178.2	64.7	59.4	3425 to 4875	1000 to 1625	Gas, L4 Gas, V6	82 at 4600 110 at 3800	M - 4 sp M - 5 sp A - 3 sp		P195/75R-14 P205/75R-14 P205/70R-14	U - 9. U - 6. C - 7.
Chevrolet S10 Blazer 4 x 2	US/Cda	R	100.5	170.3	64.7	64.7	3800 - 4535	1000 Nominal	as	above	M - 4 sp M - 5 sp A - 4 sp		P195/75R-14 Larger sizes optional	
Datsun Pick-up	Japan	R	101.4 110.8	171.7 187.0	63.4	61.2	4250 to 4800	1100 to 1800	Gas, L4 Diesel 4	98 at 5200 61 at 4000	M - 4 sp M - 5 sp A - 3 sp		700 x 14 E78 - 14	C - 8. I
Dodge Rampage	US/Cda	F	104.2	183.6	66.8	51.8	3450	1135		87 at 5200	M - 4 sp A - 3 sp		P175/75R-13 P195/60R-14	
Dodge D50	Japan	R	109.4	184.6	65.0	60.6	~~4015~~ 3590 lb 1520	~~1335~~ 1110 lb 1620	Gas 4 2 l.		M - 4 sp A - 3 sp			
Ford - Ranger	US/Cda	R	107.9 113.9	175.6 187.6		66.7	3760 to 4460	1000 to 1755	Gas 4	79 at	M - 4 sp M - 5 sp A - 3 sp		P185/75R-14 to P205/75R-14	
Mazda - B2000	Japan	R	107 113	180 191	63	61	4000	1400	Gas 4	77 at 4300	M - 5 sp		P195SR-14	C - 7.
Toyota - Pick-up	Japan	R	101.9 110.2	171 186	66.5	58.9	3924 to 4550	1400 to 1950	Gas 4 Diesel 4	100 at 4800 62 at 4200	M - 4 sp M - 5 sp A - 4 sp		700 - 14 7.50 - 14	
Volkswagen Pick-up		F	103.3	161.9	63.6	53.4	3000	950	Diesel 4	52 at 4800	M - 5 sp		P165/70R-13 P175/70R-13	C - 5.
Suzuki SJ410	Japan	4 x 4	80 93.5	135.4 153.1	57.5	66.1	2676 to 3075	747 to 1124	Gas, L4	45 at 5500	M - 4 sp 2 sp transfer		FR78 - 15	V - 9. U - 7.
Chrysler	Cda	F	112	176	69	65	4400	1700	Gas 2.0L Gas 2.6L		M - 5 sp A - 4 sp A - 3 sp		P195/75R-14 P205/70R-14	

5.2. Selection of Reference Vehicle

The techniques used to evaluate performance and economic factors require that an existing commercially available internal combustion engine powered vehicle be selected as a reference vehicle.

This reference vehicle should be capable of economical performance in the roles set out in Section 3.2 and as close as possible to the dimensional characteristics and performance set out in the Preliminary Performance Specification in Section 3.3 i.e.: -

- passenger/cargo vehicle
- maximum seating capacity - 4 persons
- overall length 350 - 450 cm
- overall width 150 - 165 cm
- wheelbase 250 - 270 cm
- curb weight 1300 - 1500 kg
- payload 350 - 400 kg
- gvw 1700 - 1750 kg
- top speed 95 - 105 kph

A review of currently available North American and Japanese vehicles indicated that the new Chrysler T115 Van/Station Wagon has dimensional and payload characteristics very close to the proposed vehicle.

Configuration	Chrysler T115 Passenger/Cargo	Proposed 4x2 Passenger Cargo
Seating Capacity	4-8	4
Length (cm)	447	350-450
Width (cm)	175	150-165
Height (cm)	165	150-165
Wheelbase (cm)	284	250-270
Curb Weight (kg)	1225	1300-1500
Payload (kg)	771	350-400
Gross Vehicle Weight (kg)	1996	1700-1750
Cargo Volume (m^3)	3.6	1.42-2.0

The Chrysler vehicle has dimensional characteristics very close to those of the propsed hybrid vehicle. It is 10 cm wider than the "acceptable" width, has a lower curb weight and a higher maximum gross vehicle weight. Although it provides a greater cargo volume than required the body configuration is very close to that required for the

hybrid. For the purposes of the evaluation the Chrysler T115 Van/Station Wagon is deemed to be an appropriate reference vehicle.

5.3 Selection of Propulsion System Components

5.3.1 Heat Engine

Previous calculations (see Section 5.1.4) indicate that a heat engine rated at 40 to 45 horsepower is required for the hybrid vehicle.

This engine must have the following attributes:

- Low specific weight (lb/hp) as the hybrid vehicle has an inherent weight penalty
- Good fuel efficiency
- Water cooled
- Commercial availability in the 40 to 45 hp range
- Capable of being serviced at commercial outlets
- Reasonable first cost and life-cycle costs
- Be designed for automotive duty in terms of duty cycle and operating conditions (temperature, vibration, emissions, etc.)

The choice of engine is severely restricted by the limited commercial applications for automotive types in the 40 - 45 HP range. Table 5-3-1, adapted from a recent study, sets out the advantages and disadvantages of various types of heat engines which might be condsidered for the hybrid power plant. Of the engines presented only reciprocating gosoline and diesel engines initially appeared likely to be commercially available within the time frame of the advanced hybrid.

A review of the characteristics of the engines against those required of the hybrid engine shows that, while the diesel engine offers an advantage in fuel consumption the carburetted gasoline engine is smaller and lighter for the same power. The lower fuel consumption of the diesel engine, particularly during part power and idling operation, will be partially offset by the need to operate the small gosoline engine at consistently high power factors to meet the power demands. Market factors notwithstanding the selection of the carburetted gasoline engine is justified by the need to keep the weight to a minimum and avoid adding to the weight penalty incurred by the hybrid vehicle.

Table 3-1

HEAT ENGINE TYPES

Type	Specific Weight (lb/kW)	Specific Volume (Fr^3/kW)	Advantages	Disadvantages
Gasoline (Reciprocating)				
Carburetted	5.0	0.08	Highly developed and readily available	Good but not excellent fuel economy
Fuel Injected	5.0	0.08		
Three-Valve CVCC	5.0	0.10		
Gasoline (Rotary)				
Uniform Charge	4.0	0.07	Small size and weight	Relatively high-emissions and lower fuel economy than reciprocating engine
Stratified Charge	4.2	0.07	Improved fuel efficiency over uniform change	Uncertain status of development
Diesel				
Naturally Aspirated	7.8	0.12	Excellent fuel efficiency	High weight and size, noise and NO_x emissions
Turbocharged	5.6	0.09	Reduced size and weight compared with N.A.	Response of turbocharger, difficulty in controlling NO_x, uncertainty of unregulated emissions
Stirling	7.5	0.12	Potential excellent fuel efficiency	High weight and size, uncertain status of development, high cost
Gas Turbine				
Two-Shaft	5.1	0.10	Relatively small size	Low fuel economy, high cos uncertain status of developn
Single-Shaft	4.4	0.09	Small size and weight	Not developed as an automo engine, high cost

An investigation of existing suitable gasoline automoile engines of 30 to 50 horsepower resulted in the identification of the engines shown in Table 5.3.2.

Of the engines listed only the 0.97 litre Suzuki and the 1.0 litre British Leyland engines are sold and serviced in Canada at present. The British Leyland engine is an old design which is being replaced in the United Kingdom by a new engine: there are at present no plans to market the new engine in Canada. Only the 1.0 litre Suzuki, therefore, comes close to meeting all the requirements. Should this engine prove unsuitable it will be necessary to move to the engines of 1.3 to 1.4 litres with reduced fuel economy or to import a suitable engine.

Appendix F reviews the factors influencing engine selection.

5.3.2 Electric Motor/Controller

A previous study examined in detail the types of electric drive systems suitable for use in a hybrid vehicle.

The motors fall into two broad categories; DC and AC. DC motor configurations include series wound, separately excited field, and permanent magnet. Candidate AC motor types include induction and synchronous (wound rotor, permanent magnet and inductor). The power and control characteristics of the motor determine the type of controller which must be used between the battery and the motor to permit the operator to modulate the motor speed/power. Presently most electric vehicles use DC series wound motors, although in higher speed automotive applications, DC separately excited motors are more efficient, exhibit lower battery current draws, and allow speed modulation via field control rather than armature control. Due to their good availability, series DC motors are widely used in electric vehicles, in combination with chopper-type aramature current controllers.

Alternating current drive systems have been considered for use in hybrid vehicles. These systems are attractive because of the fact that the AC motor is smaller and lighter than a DC motor of the same power and mixiumum rpm. This advantage is further enhanced by raising the AC motor rpm, due to the electronic commutation. In the DC motor, maximum rpm is limited by bounce and wear of the commutators bars and brushes. Also, AC motors are presently produced in large volumes for commercial and residential use and therefore cost less than equivalent power DC motors. The major disadvantage of the AC drive system is that it requries a complex/expensive inverter between the DC batteries and the AC motor. AC motors of the size required for the hybrid vehicle operate on

polyphase current (3 phase), increasing the cost and complexity of the DC to 3 phase AC inverter. Presently no suitable inverter (in terms of size, weight and cost) is commercially available, although recent technological developments may permit the development of such an item in the near term.

Table 5-3-5 presents the advantages and disadvantages of each of the candidate motors. Based upon the factors indicated in Table 5-3-5, only three motors are considered as contenders for the hybrid vehicles:

- DC series
- DC separately excited
- AC induction (wound rotor and stator).

In examining the weight of the electric motor, the controller weight must also be factored in, to make valid comparisons. Table 5-3-6 lists the motor and controller weights for the various electric motors considered. The lightest combination is the high speed AC motor at 8.0 lbs per kw, while the heaviest is the DC seris motor at 15.4 lbs per kw: for a 20 kw motor, the corresponding motor/controller weights would be 72 kg and 140 kg. Note that, unlike heat engines, electric motors are rated in terms of continuous power levels. DC separately excited motors, unlike DC series motors, tend to maintain their torque output at higher rpm, and field weakening can be used to reach higher rpm.

Table 5-3-7 presents the efficiency of AC and DC motors and controllers. While the AC motors are more efficient than their DC counterparts, the inverse is true of their controllers.

In conclusion AC motors are 4 to 6% more efficient than DC motors, particularly under heavy load conditions. However, this is partially offset by the more efficient controllers used with DC motors, including armature current choppers. The net result is that the DC motor/controller combination is approximately 2% less efficient than AC under heavy load conditions.

5.3.3 Motor Power and Speed Characterisitics

It is desirable that the motor have a maximum speed equal to that of the proposed heat engine to allow the use of a single shaft design if this proves feasible. Typical gasoline engines in the 30 - 35 HP range will normally have maximum speeds in the region of 5000 - 5550 rpm and the motor should match this.

TABLE 5-3-2

Candidate Gasoline Fueled Engines

Item	Manufacturer	Model	Displacement (l)	No. of Cyl.	No. of Cycles	Peak hp	Peak torque kg-m	Max. rpm	Weight
1.	Subaru		0.54	2	4	31 at 6000	4.4 at 3500	6000	
2.	Mitsubishi	Vulcan-S	0.55	2	4	29 at 5500 31 at 5500	4.2 at 3500	5500	
3.	Diahatsui	CB	1.0	3	4	55 at 5500	7.8 at 2800	5500	86 kg
4.	Diahatsui	AB 30	.55	2	4	29 at 6000	4.0 at 3500 (29 lb ft)	6000	64 kg
5.	Suzuki		0.797	4	4	41 at 5500	6.1 at 3500 (44 lb ft)	5500	
6.	Suzuki		0.97	4	4	45 at 5500	7.5 at 3000 (54.2 lb ft)	5500	
7.	Fiat		0.90	4	4	45 at	6.5 at 3000		
8.	British Leyland		1.0	4	4	40 at 4800	7.4 at (52 lb ft)	5000	

Table 3-5

ELECTRIC DRIVE MOTORS CONSIDERED FOR HYBRID VEHICLES

Type	Example	Status	Advantages	Disadvantages
DC Series	GE BT2366	Production	No separate field excitation required, high torque at low speeds, easy to control	Large torque decrease at high speeds is difficult to control. Regeneration requires reversal of field windings
DC Separately Excited	Modified version of GE BT2366 for use in DOE/SPL NT electric car available also from Bosch, Siemens, and Lucas	Limited production	Control flexibility ease of achieving regenerative braking	Relative complexity of construction, maximum rpm limited by commutation
AC Induction (wound rotor and stator)	GE test motor in NASA contract No. DEN. 3-59, Max rpm - 12,000	Laboratory testing	Small size and light weight, lower cost	Requirement for complex three-phase inverter
AC Permanent Magnet Synchronous Disk Motor	GE test motor on CRD funding	Laboratory testing	Small size and lightweight, high-efficiency load-commutated	Difficult to start and control due to very low reactance, requires three-phase inverter, cost uncertain

Table 5-3-6

Weight and Size Characteristics of Electric Drive System Components

	Motor*		Controller**
Drive Type	lb/kw	ft^3/kw	lb/kw
DC - Series Motor	14.2	0.075	1.2 (1.9)***
DC - Separately Excited Motor	12.3	0.075	1.2 (1.9)
AC Induction Motor			
- low speed (5000 rpm)	7.7		2.4 (3.9)
- high speed (12,000 rpm)	5.6	0.045	2.4 (3.9)
AC PM Synchronous Disc Motor	5.6		4.8 (3.5)

* Motor is rated at continuous (1 hr) power (kw)
** Controller is rated at peak power (kw)
*** A(B); A - weight using transistors, B - weight using thyristors

Table 5-3-7

Electric Drive System Efficiency at High Loads

	Efficiency (%)		
System Type	Motor	Controller	Combined
DC Separately Excited	88	97	85
AC Induction	93	94	87
AC PM Synchronous	92	93	85

When operating in the all electric mode the hybrid vehicle should be capable of a sustained cruising at 65 kph in top gear. To achieve this with the vehicle defined in Section 3.2 the motor must be capable of producing at least 9 HP continuously at 3300 rpm drawing power from batteries of nominal 60 volts. The preliminary motor characteristics are:

Continuous duty rating	10 - 12 HP at 3300 rpm
Maximum speed	5500 rpm
Rated voltage	60V

5.4 Design Concept

The development of the design concept may be approached either as a "ground up" design of a completely new vehicle in which a significant proportion of the components employed are designed and built specifically for the hybrid, or as a conversion of an existing vehicle design.

The first course allows the vehicle designer freedom, within the various statutory requirements, to tailor the vehicle precisely to the specification. The design and development of special components such as those for new suspension systems is, however, likely to be a lengthy and costly undertaking and the production costs of special components in relatively small quantities will be high. These costs may be reduced to some extent by using component parts developed for other vehicles and adapting them to the environment created by the hybrid vehicle. The extent to which it is possible to negotiate "Original Equipment Manufacturer" (OEM) prices with suppliers for such components will also affect unit prices. If this course is adopted the vehicle manufacturers will be required to underwrite the cost of whatever warranty is provided, negotiating offsetting agreements with component suppliers to the maximum extent.

The development of a "ground up" design will entail qualification of the vehicle against the Canadian Motor Vehicle Safety Standards probably involving modification and design changes. This, in itself, may prove a major undertaking.

The conversion of an existing vehicle to an electric hybrid removes the freedom of the designer to develop against the requirements of the specification and introduces the need to compromise on some of the major requirements.

The minimum change required in a conversion program entails the removal of the vehicle power plant and the substituition of a smaller engine and an electric motor. Batteries and control equipment must then be added. The net result of these changes is an increase of 480 kg or

more in the curb weight of the vehicle. A reserve load carrying capacity of this magnitude is not normally found in passenger cars and considerable design changes are required when converting such vehicles. It is frequently necessary, therefore, to use a cargo carrying vehicle of suitable load capacity as a basis for conversion.

If a suitable load carrying vehicle is available its conversion may involve considerable body building work and adaptation to passenger carrying roles may prove difficult. While there has been some recent improvement vehicles of this type are not, as a rule, designed to provide the fuel efficiency of the passenger vehicle particularly in regard to aerodynamic drag: the amount of corrective development which is practicable in this area is strictly limited.

In converting an appropriate vehicle little change other than outlined above should be required and, providing the operating environment of the original components is not made more severe, it should be possible to negotiate with the vehicle manufacturer to underwrite the warranty on the same terms as for the vehicle in its original form. Similarly, if the installation of the new equipment is carried out with reasonable skill no problems should be encountered in meeting mandatory safety standards.

If a suitable vehicle is available and the compromises of specification requirements are acceptable the conversion of an existing vehicle is likely to prove a far more economical course to adopt than the "ground up" design of a new vehicle. The ability to make use of fully developed componentry in the environment for which it was designed will yield generally more satisfactory results than the extensive incorporation of new designs. It will still be necessary to undertake development of some components, particularly those associated with the replacement drive line components and the major development activity should be in this direction rather than in other areas where satisfactory production components are available.

5.4.1 Selection of Vehicle for Conversion

There are a number of light pick-up trucks such as the Cheverolet S10, Ford Ranger and Datsun and the new Chrysler T-115 Van, all of which have load ratings in the appropriate range and could be conomically converted to hybrid vehicles. The pick-up trucks are equipped with two/three passenger cabs and an open box and it would be necessary to develop a specialist cab/body to adapt them to the roles set out in Section 3.2. The new Chrysler vehicle would require little or no change to the body and, while the cramped engine compartment normaly associated with front wheel drive vehicles may make the power train installation more difficult, it is judged the most suitable

candidate for conversion at this stage. There is little published data available and that recorded in Table 5.1.5 and elsewhere in this report was obtained informally from the Chrysler Corporation.

The gross weight of a hybrid vehicle with 350 kg payload based on the Chrysler van is estimated at 1897 kg in Section 5.1. This is approximately 100 kg above the maximum specification level. In all other significant respects except overall width where the Chrysler vehicle exceeds the specification limit by 10 com it meets the requirements of the performance specification.

The vehicle provides about 1.5 times the cargo volume required by the specification at its maximum rated gross weight of 2,000 kg and would be capable of carrying a payload of 495 kg when converted to a hybrid.

It is anticipated that both General Motors Corporation and the Ford Motor Company will follow the Chrysler lead and introduce similar light vans over the next two years allowing a wider choice of base vehicle within the overall time frame of the project.

5.5 Operation in Winter

Most of Canada experiences a severe winter with ambient temperatures falling well below zero. Chart 5.5.1 illustrates the normal and extreme daily temperatures at Ottawa. The Ottawa conditions are typical of much of Eastern Canada and temperatures of -30°C and lower may be expected during a 3 month period during the winter; temperatures in the Prairie Provinces may run about 10 degrees below those for Ottawa. At these temperatures motion resistance will increse and provision for heating the passenger compartment must be made. The usable capacity of the battery will diminish unless some provision is made for heating when the vehicle is parked outside for extended periods. The control strategy must be suitable for operations in winter. Of the principal motion resistances tire rolling resistances and mechanical power transmission losses will be affected significantly by ambient temperatures in the anticipated ranges.

5.5.1 Tire Rolling Resistance

Tire rolling resistance has been shown to increase dramatically when the temperature of the tire is reduced. The resistance falls rapidly, however, as the tire is warmed by opertion and tends to stabilize after 15 minutes of operation at 80 km/h at a level which, while much lower than the initial resistance, is still considerably higher than the value experienced at higher ambient temperatures. The temperature at which the tire will stabilize depends

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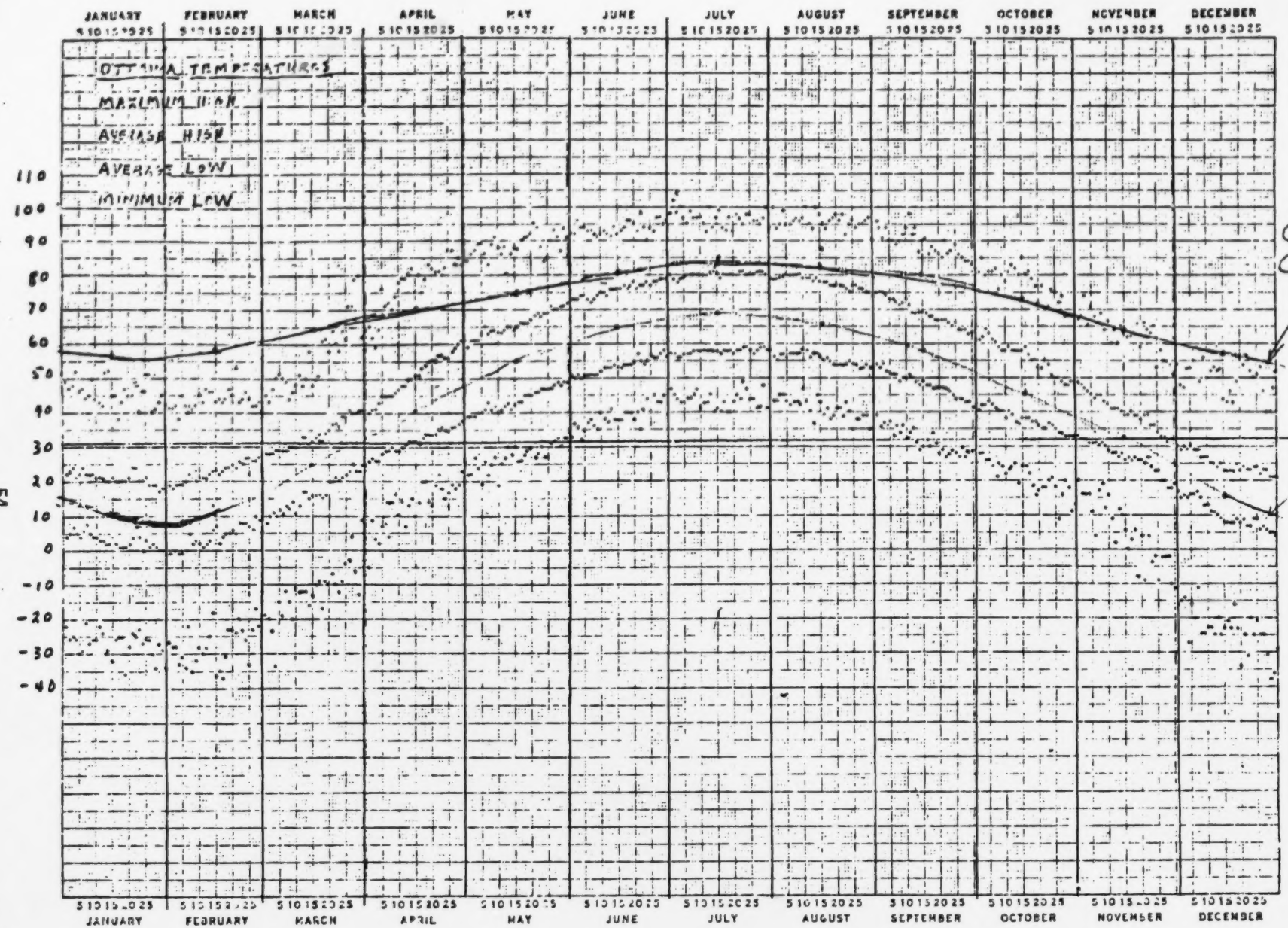


Chart 5.1

upon the ambient temperature and the speed at which the vehicle is operated.

- the power required to overcome tire motion resistance at -30°C when the vehicle is operated at 80 km/h (50 mph) on the highway will be about 50% greater than that required at +20°C; and

- the power required to overcome tire motion resistance at -30°C when operating over urban roads at an average speed of 32 km/h (20 mph) is about 90% greater than that required at +20°C.

5.5.2 Drive Train Losses

There is little published data on the effect of low temperatures on losses in vehicle drive trains. Mechanical and fluid friction in the gear boxes will warm the fluids and components and initially high losses will be reduced as the vehicle is operated. It appears probable that the losses in the vehicle drive train will be 30 - 40% greater at -30°C than at +20°C. The actual figure will depend upon component design.

5.5.3 Effect of Increased Motion Resistances

The estimated power required to propel the proposed hybrid at temperatures of -30°C and +20°C are shown in Appendix B. The increase in power required will result in significantly higher energy consumption at the lower temperatures.

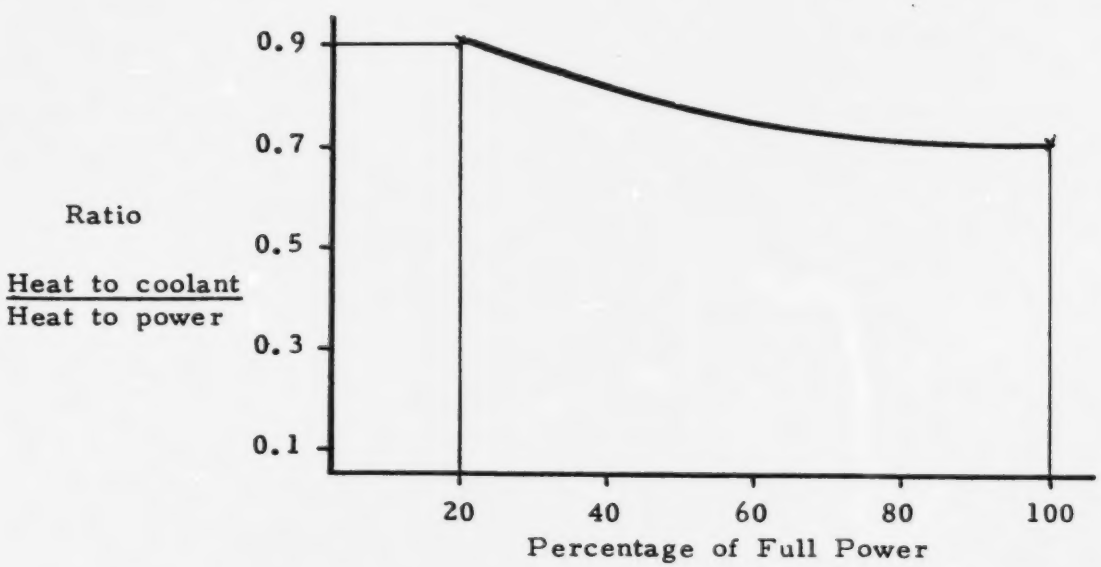
5.5.4 Heat Required for Passenger Compartment

For safisfactory operation in the Canadian winter the heater should provide sufficient heat to the passenger compartment to raise the temperature ot comfortable level within 15 minutes when the vehicle is cold soaked to -20°F. Using methods adapted from track practice, (Appendix B) the minimum heater capacity required to meet this criteria is about 40,000 BTU/hour.

5.5.5 Heat Rejection From Engine

A typical Otto cycle engine operating a full throttle converts about 33% of the fuel heat to work and rejects another 30% to the coolant, a further 35% is rejected with the exhaust gases. The ratio of the heat to coolant to the

heat to power varies somewhat with the power level at which the engine is operated, see below.



If the engine is to provide 45,000 BTU/h to the coolant to drive a 40,000 BTU heater it will have to operate at approximately 20 BHP output.

Preliminary computer runs indicate that the heat engine provides a mean output of about 3 HP when the vehicle is operated as a hybrid over the EPA urban cycle using a control strategy designed for optimum fuel economy under summer conditions. The means total power used during this cycle is about 12 HP. In winter operation at -20°C the mean total power required for the urban cycle is estimated at 18 HP. With a revised control strategy it is possible that approximately 15 HP will be provided by the heat engine and the remainder by the electric motor. It is apparent that about 75% of the required heat would be available from the coolant in these conditions.

When the vehicle is operated over the highway most of the power required is provided by the heat engine and it will operate at levels close to those required to provide the heat required.

It may be necessary, therefore, to provide additional heat to supplement that available from the engine coolant during urban operation: this will amount to about 25% of the passenger compartment heating load in extreme winter conditions.

5.5.6 Methods of Supplementing Coolant Heating

The following techniques are available to provide heating of the passenger compartment:

- Use of fuel fired heater to supplement engine heat
- Use of engine exhaust heat
- Revision of control strategy to provide full time heat engine operation
- Use of engine generated electric heat

These are discussed below.

5.5.6.1. Fuel Fired Heater

Fuel fired heaters are available either as coolant heaters or as space heaters. The former are normally used as engine preheaters for low temperature operation. In the interest of maintaining fuel economy a hot water passenger compartment heater will be installed in the hybrid vehicle for use in conditions where sufficient engine coolant heat is available to meet the requirements. The use of a coolant type heater either connected directly to the engine block or inserted in the heater lines provides a suitable means of supplementing engine coolant heat. Such an arrangment would also maintain the engine at a suitable operating temperature during periods of shut down.

The fuel fired space heater offers greater flexibility in heat output than the coolant type, however control is likely to pose some problems. There will also be problems in locating two heaters in a relatively small compartment.

Fuel fired heaters of the flame type operate at an overall thermal efficiency of 50 - 60% depending on operating conditions. Pulse-resonance combustion heaters (e.g. Swingfire) have a substantially higher efficiency under most conditions.

5.5.6.2 Exhaust Heat

As has been noted above the engine rejects about one third of the fuel heat with the exhaust gases. The recovery of a portion of this heat to assist in heating the passenger compartment is possible by either water jacketing a part of the exhaust system or by circulating passenger compartment air over some part of the system. The latter arrangement creates risk of CO contamination of the air and will not be considered.

It is estimated that up to 75% of the heat in the exhaust gases could be recovered by enclosing the exhaust manifolds and/or a portion of the exhaust pipe close to the engine in a water jacket connected to the engine coolant - circulation system.

The following problems would arise:

- Exhaust temperature would be lowered to the point where excessive condensation would occur creating very corrosive conditions in the exhaust system.

- It would not be possible to use a catalytic converter of current types to reduce emissions because of low exhaust gas temperatues.

- The load on the cooling system in summer would be increased by about 75%.

The significance of these problems will depend on the detail design of the vehicle. Thus, the presence of a hot exhaust system in close proximity to batteries and traction motors complicates the problem of cooling these components during summertime operation: this problem would be alleviated if the exhaust was water cooled.

5.5.6.3 Revision of Control Strategies

It has been demonstrated that for optimum fuel economy under normal urban operating conditions the heat engine should provide about 25% of the energy required to propel the vehicle and operate at relatively high power factors for short periods of time. In a vehicle of the type of the hybrid under consideration the heat engine would operate at a mean power level of about 3 HP in urban conditions. During winter operation all the coolant heat will be dissipated in the engine compartment by radiation and convection or wind chill and the passenger compartment must be heated by a fuel fired heater. Assuming that a steady heat input of 35,000 BTU/h is required at -20 ^{o}F after initial warm up the heater will burn about 1.8 litres of gasoline per hour. This would result in a dramatic decrease in fuel economy from 2.8 l/100 km to about 8.2 l/100 km. At higher temperatures the loss of economy is less dramatic but still significant.

If the control strategy is changed to allow the vehicle to derive 90% of the power required during the EPA urban cycle from the heat engine it is estimated that the fuel consumption would be 6.3 l/100 km. The engine will provide about 25,000 BTU/h to the coolant and the heater must provide the remaining 10,000 BTU/h for operation at -20 ^{o}F. The resulting fuel economy is of the order of 8.4 l/100 km.

It is apparent that, while the overall energy consumption will be reduced by revising the control strategy to draw more power from the heat engine there is little effect on hydrocarbon fuel consumption. It may still be necessary, however, to increase the engine duty to ensure that reasonable engine and engine compartment operating conditions are maintained during low temperature operation.

5.5.6.4 Engine Generated Electric Heat

The engine has more power available than is required to drive the vehicle during urban operation. It is possible to make use of the excess power to generate electricity by operating the motor generator in the generator mode and to use the electric power to provide heat to the passenger space. A control strategy is required which ensures that the heat engine provides most of the power to propel the vehicle while operating at a power level sufficient to provide the power required by the generator. The conversion of the excess fuel energy to heat would be at about 60% overall thermal efficiency or about the same as for the fuel burning heater and the effect on energy and fuel consumption would be about the same as discussed in 5.5.6.1.

5.5.7 Discussion

The most economical method of providing sufficient heat to the passenger compartment appears to be a revision of the control strategy so that the engine provides 90% of the energy required to propel the vehicle under urban conditions. If under the new strategy the engine is allowed to idle during non-driving periods sufficient heat output should be provided to maintain satisfactory conditions in the passenger compartment although the warm-up time may be greater than 15 minutes.

Should it be necessary to further enhance the heater performance the most economical course would be to utilize some of the heat rejected with the exhaust.

5.5.8 Conclusion

It is concluded that:

- Tire rolling resistances will increase by up to 90% when the vehicle is operated under urban conditions at -30°C and
- the most economical way of providing passenger compartment heating is by changing the control strategy to allow the heat engine to provide 90% of the power required for urban operation.

6. OUTLINE SPECIFICATION OF HYBRID VEHICLE

6.1 General

The proposed vehicle is a conversion of the Chrysler T115 light van (Caravan) introduced in the 1984 model year. The vehicle outline, compared with that of the Chrysler Aries (K car) station wagon and the current full size Chrysler B150 van is shown in Figure 6.1. Figures 6.2 and 6.3 illustrate the locations of the heat engine/electric motor/transmission assembly and the battery pack as well as the cargo area.

In the conversion process the original engine is removed, the transmission is modified and the hybrid power train is installed. The exhaust system, fuel tank and spare tire are relocated to accomodate the batteries and the vehicle floor is reworked to provide battery clearance.

The resulting vehicle has a gross weight lying within that of the standard van and will have identical exterior dimensions.

6.2 Major Components

6.2.1 Power Package

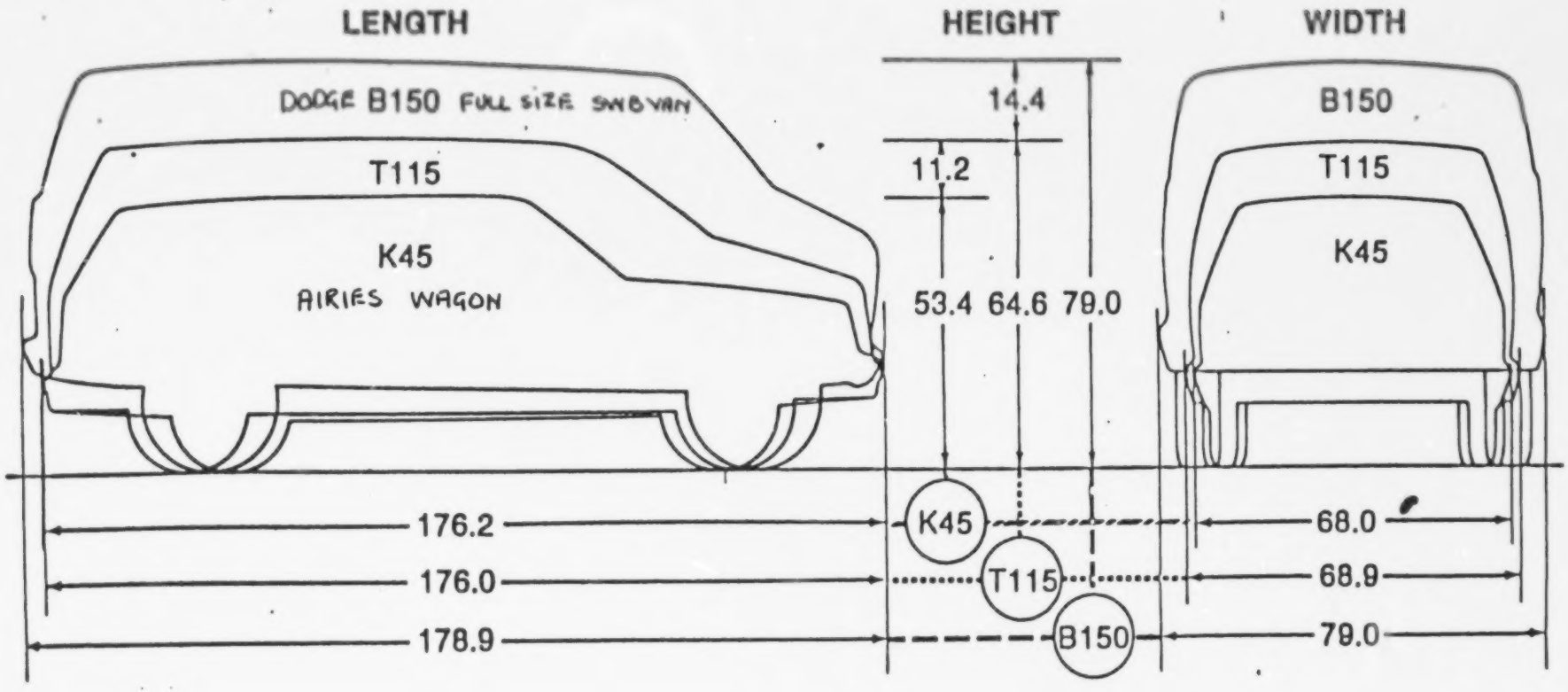
Type - electric motor, gosoline engine hybrid, two shaft, parallel arrangement

Electric Motor	-	15 Kw rated, 24 Kw peak power
	-	base speed 3200 rpm
	-	max. speed 8,000 rpm
	-	separately excited 100-120V DC
*Motor Controller	-	electronic armature chopper with field chopper, with field reverse capability
*Motor Transfer Drive	-	Morse Hyvo chain, special case 1.3:1 reduction
Engine	-	3 cylinder gaosline, 993 cc displacement
	-	peak power 41 Kw at 5500 rpm
	-	max. torque 7.8 kg at 2800 rpm
	-	dry weight 86 kg

FIGURE 1

CHRYSLER T115 VAN

SIZE PERCEPTION/RELATIVITY



DIMENSIONS IN INCHES

Figure 6.1

Figure 6.2

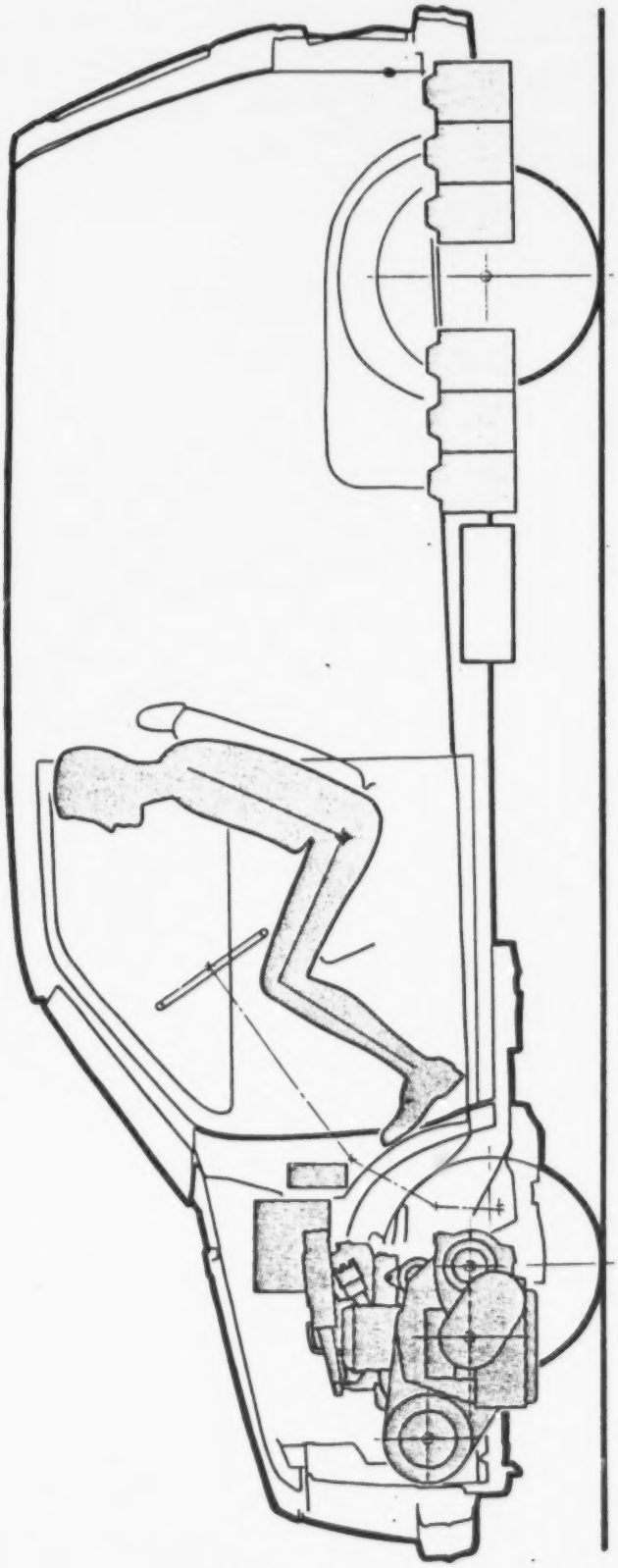
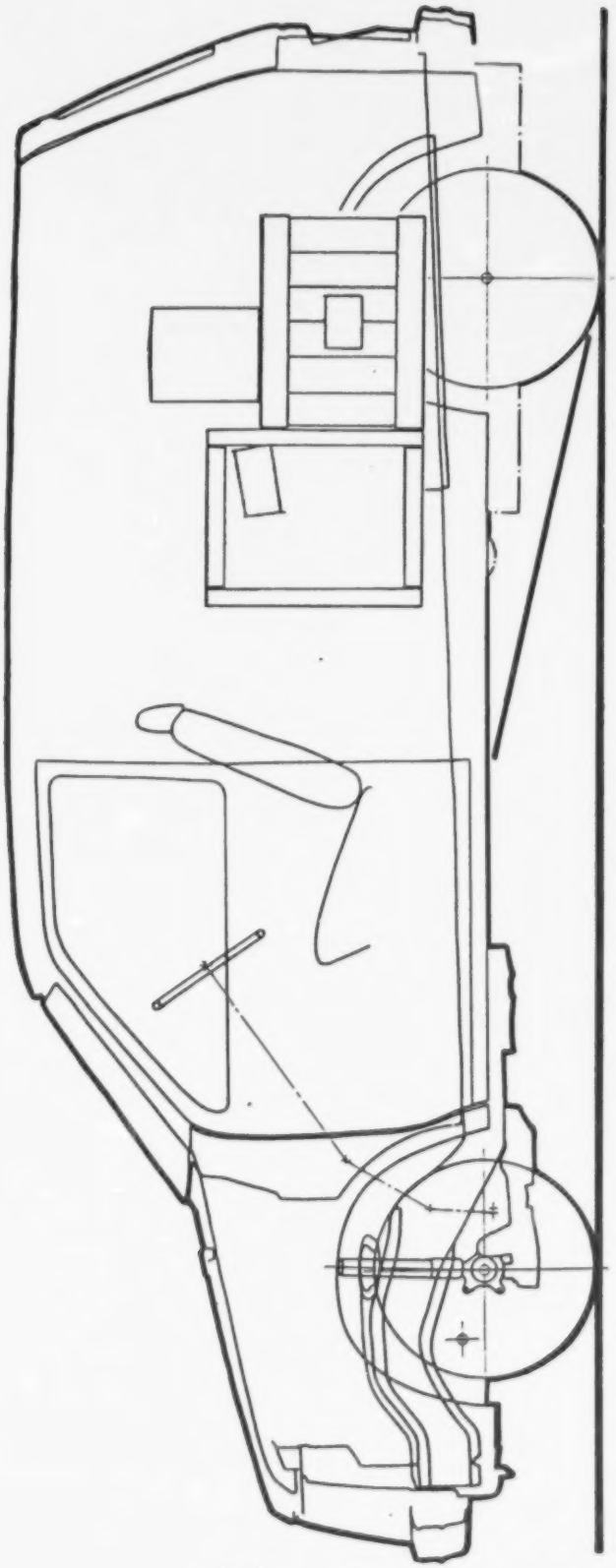


Figure 6.3



6.2.2 Other

*Engine Clutch	-	single plae, dry clutch hydraulic actuation, toggle engagement
*Transmission	-	Chrysler 3 speed automatic without torque convertor. Modified to increase final drive reduction and allow modulation of shift points by control system. Rations 2.84, 1.6, 1.0:1 Final Drive 5.2:1
Transmission and Steering Pump Service Motor	-	1 Kw 100-120V DC Series wound
Fuel System	-	25 litre fuel tank mounted on left side of vehicle
Exhaust system	-	redesigned system to right side of chassis, longitudinal muffler with rear discharge
Brakes	-	hydraulic, Bendix hydroboos hydraulic power assist
*Service Electrical System	-	12V DC
	-	12V, Group 24 battery
	-	100-120V - 12V DC to DC converter
Traction Batteries	-	10 x 12V batteries with single point watering system
	-	16 KwH stored energy
	-	corrosion resistant battery boxes
	-	batteries located ahead and behind rear axle
*Vehicle Control System		- microcomputer based system providing control of mode selection, power sharing, regenerative braking and operating point of engine. (An outline of the proposed system is contained in Appendix G)

Instrumentation - new instrument cluster to display additional data

NOTES:
1. Items not specifically identified above will be as fitted to the standard base vehicle.
2. Items marked * will require significant developement work.
3. Appendix F documents market surveys undertaken to evaluate available componentry and outlines components which would have to be designed and built by the vehicle converter or a supplier.

6.3 Dimensional Characteristics

Length (cm)	447
Width (cm)	175
Height (cm)	164
Wheelbase (cm)	284.5
Turning Circle - diameter (m)	12.5
Gross Weight (kg)	2030
Payload (kg)	350

6.4 Performance

Range (gasoline) on highway (km)	300
Cruise speed (km/h)	95
Maximum speed (km/h)	105
Acceleration 0-50 km/h (secs)	9.0
0-90 km/h (secs)	24.0
Gradeability at 50 km/h	>8%
Maximum	>20%

6.5 Energy Consumption (Averages)

Distance km	Gasoline Used (l)	Electric Energy Used (Kwh)
40	1.28	7.45
80	3.44	9.45
120	7.02	10.7

7. COMPLIANCE WITH CANADIAN MOTOR VEHICLE SAFETY STANDARDS (CMVSS)

7.1 General

The propsed hybrid vehicle will be based on a standard commercial van which in its normal configuration may be assumed to meet all the requirements of the Canadian Motor Vehicle Safety Standards (CMVSS).

7.2 CMVSS Requirements

7.2.1 Weight Factors

In the conversion process some components will be removed and replaced by new equipment and others will be relocated, new equipment will be installed and the curb weight will be increased. The payload of the converted vehicle will be restricted to a level such that the gross weight will not exceed the maximum accpetable level established by the vehicle manufacturer. The batteries which form the largest portion of the added mass will be located so that the front/rear axle load distribution matches that of the base vehicle at the same weight.

While the addition of the motor mass forward of the front axle and the counterbalancing of this by battery mass well to the rear of the vehicle will increase the pitch and yaw inertia the magnitude of the increase will not be large. The effects on the ride and handling characteristics of the vehicle should not be greater than that experienced with certain types of loading commonly applied to a van of this type.

7.2.2 Crash Worthiness

The hybrid conversion vehicle should have approximately the same characteristics as the basic van. The installation of the electric motor ahead of the engine may reduce the effective crash length somewhat but at this stage the reduction does not appear likely to seriously impair the crash worthiness of the vehicle.

7.2.3 Fire Protection

The CMVSS are based on the requirements for standard internal combustion engined vehicles. In installing the new gasoline tank it will be necessary to ensure that the chances of fuel spillage due to either roll over or tank crashing is reduced to the acceptable level. The detailed design of the electrical propulsion system must incorporate suitable safety devices (fuses, current limiters, thermal cutouts, etc.) to reduce the fire hazard from short circuited or over heated electric components to a minimum.

7.3 Additional Safety Requirements

The use of an electtric propulsion system introduces safety hazards not dealt with by the CMVSS. These are dealt with briefly below.

7.3.1 Battery Retention

The traction batteries must be mounted in a fashion which ensures that they do not break loose when the vehicle is involved in a collision. It is intended that the batteries will be mounted beneath the floor of the van and secured directly to the vehicle frame.

7.3.2 Battery Explosion

Bateries will be equipped with "explosion proof" caps and positive ventilation of the battery box(es) will be provided. Spark arresting connectors will be employed when required. Special attention will be paid to the problems arising from regenerative braking when the batteries are at full charge.

7.3.3 Electrolyte Spillage

Precautions will be taken to ensure that electrolyte spillage as a result of accidents does not enter the vehicle passenger/cargo space.

7.3.4 Electric Shock

A battery disconnect switch will be intalled to allow the batteries to be isolated for vehicle servicing and an interlock will be fitted to automatically disconnect the batteries when the battery compartment is opened.

7.4 Conclusion

With a few exceptions the hybrid vehicle will possess the same safety characteristics as the basic van. Careful attention to detail design should provide a vehicle capable of meeting all the CMVSS.

8. HARDWARE DESIGN

Major hardware components designed or modified will include -

1. Vehicle Propulsion System Controller (VPSC)

2. Motor Controller with regenerative braking capability at entire range of motor speed

3. Computer (VPSC) modulated automatic transmission and clutch

8.1 Computerized Vehicle Propulsion System Controller (VPSC)

This propsed system is aimed at minimizing energy consumption automatically without sacrificing ease of driving and comfort. Since the hybrid vehicle carries two completely different power sources, blending or switching from one to the other is the major task of this system and is automatically done without any noticeable jolt.

Other functions of the VPSC include:

a) battery Depth of Discharge (DOD) monitoring
b) battery charge control according to DOD and surplus power
c) transmission modulation together with clutch modulation
d) driver compartment heating control
e) indication of vital information on instrument panel
f) hardware failure detection and selection of counter measure

The control system is designed to provide a complete and precise control of the major functions of the propulsion system to ensure efficient and economical operation of the vehicle.

Details of the VPSC program specification, its description and source code list are contained in Appendix H.

8.1.1 Operating Principle

The system is micro-computer based. Information on the operating conditions of the propulsion system is collected from appropriate sensors by a data acquisition system. The raw data is passed through a memory bank to the main computer where it is compared with standard reference data and decisions on changes to be made in the operation of the various sub systems are taken. The decisions are implemented by commands passed to the appropriate actuators

or to indicators in the case of items requiring operator action.

The functioning of the control system may be illustrated by considering the sequence of events in a typical driving schedule.

a) The vehicle is at rest with the power turned on; the driver depresses the accelerator pedal and the control system passes the demand for torque to the electric motor. The vehicle accelerates.

b) When the vehicle reaches the speed (V mode) at which the heat engine may operate economically the control system issues a command to start the heat engine. This command engages the engine clutch and sets the throttle stepping motor at an appropriate starting setting for the speed. When the engine starts the throttle setting is changed to provide the torque demanded and the electric motor is shut down. The control system monitors the state of charge of the traction batteries and the speed at which the mode change takes place is reduced as the energy in the batteries is depleted.

c) If the driver demands more torque than can be provided by the propulsion mode in use, the control system will command the second power source to supply power. The system will proportion the power provided by the electric motor and the heat engine so that the heat engine always operates as close to its optimum economy line as possible. When the driver reduces the torque demand to the appropriate level the control system shuts down the power source which is no longer required; the control system incorporates a hysterisis which avoids the development of a "hunting" condition.

d) With the vehicle travelling at speed and if the driver fully releases the accelerator pedal the control system disengages the engine clutch and instructs the motor to act as a generator providing the same level of resistive torque as would be provided by an engine of appropriate size for the vehicle. The energy thus generated is used to charge the traction batteries; initial application of the brake pedal increases the regenerative action. The control system also overrides the automatic transmission during braking and commands a shift into the lowest appropriate gear to maintain maximum generator speed for efficient generation. With this automatic shift down, it is possible to decelerate down to 4-5 kph

without the help of mechanical brake.

e) As the vehicle slows down the control system ensures that if the speed falls below the mode change level, the necessary commands are issued to activate the electric motor.

f) When the battery energy becomes depleted after extensive operation and the state of charge falls below 0.28 the control system institutes a change in the operating mode so that any surplus power which may be available when the heat engine is operated at its most economical level is used to drive the generator (motor) and to recharge the batteries. When this happens the controller ensures that demands to meet vehicle propulsion requirement are given priority over battery recharging. If the state of charge falls below 24% the controller demands maximum heat engine power and provides limited priority for battery recharging over road operation.

If the state of charge should fall below 20%, the electric motor no longer powers the vehicle, but only generates electricity, and in this case, low charge warning lights up informing driver that the electric motor is currently not available.

g) During winter, V mode is lowered to minimal so that heat engine almost always operates as power source except for at very low speed. Also the engine keeps idling even if no power is requested. This ensures sufficient heat be provided by the engine. The electric motor joins to power the vehicle whenever torque demand for the heat engine exceeds its optimum (most economical) value.

8.1.2 Vehicle Control System Components and Connection

Major parameters to be controlled by the computer are the following:

a) electric motor armature voltage
b) electric motor field voltage
c) heat engine throttle valve opening

All control parameters except for the above three require only on and off operation. Those are:

d) electric motor field reverse contactor
e) heat engine ignition relay

f) clutch actuator valves
g) service motor
h) transaxle throttle valve overrider

Since the functions of the VPSC are many and diverse, it may appear that the vehicle is totally controlled by the VPSC, not by an operator, and if it fails the vehicle is completely immovable. This is not the case for this control systems since;

1) The system has internal hardware failure detection system and automatically deploys backup circuit.

2) Even when one of the motors fails, the vehicle can still be operated by the other motor.

3) When all electronics fails or if driver wishes manual mode, the vehicle can still be operated as either conventional gas engine powered van or electric car.

Due to all these multiple functions of the VPSC, internal software becomes slightly complicated and lengthy however it should be noted that hardware for the system is not complicated at all especially when compared with that of GE - JPL near term hybrid vehicle.

This VPSC includes approximately twice to three times as many components (sensors, actuators, etc.) as EFI (electronic fuel injection) system which is considered a relatively simple application of a computer. And, as the reliability and cost of EFI system of today shows, this slight complication will certainly become acceptable in commercial use in the very near future.

8.2 Motor Controller With Regenerative Capability

It is vital to implement regenerative braking to increase energy efficiency of the vehicle. For this reason, separately wound DC motor was selected which usually is relatively difficult to control compared with series motor.

However there seems to be no motor controller available on the market which is specifically designed for a separately wound motor. All of the controllers available had a function simply to vary duty cycle for the armature and the field hence altering effective voltage proportionally to input voltage or gas pedal position. Unlike a series motor, both the field and the armature has to be controlled separately, which is, in some occasions, next to impossible for an operator to set both parameters at optimum. This is especially true when regenerative braking is needed or motor speed is rapidly changing.

Hence the motor controller has to be controlled by a computer which instantneously and precisely determines optimum duty cycle for both circuits.

For this purpose, a little interface circuit was installed in a standard PMC Motor Controller in order that it can be modulated by the computer (VPSC) output signal.

For regenerative braking at high motor speed, field current is increased to obtain sufficiently higher motor back votage than that of the battery pack.

However when motor speed is low (lower than base speed), it becomes impossible to obtain sufficiently high back voltage from the motor even with maximum field current. Therefore some measure has to be employed to raise the back voltage to the level above the battery terminal voltage. The method selected and implemented to achieve this was the use of chopper circuit and inductance which works in a similar manner to a transformer in AC circuit. General Electric near term hybrid vehicle utilized, for this purpose, discrete chopper which solely works for regeneration. However this is obviously costly and somewhat redundant since there already is a chopper for motor drive circuit. Therefore a new idea was used which, by changing the wire connection via single contactor, enables the driver chopper to work as regeneration chopper. Inductance for raising voltage is the armature of the motor, and through several experiments, the following fact was verified.

1) The chopper initially designed for motor driving can also be used for regeneration chopper without any major modification.

2) The armature of the motor intended for vehicle propulsion has sufficient inductance for raising voltage with a chopping frequency of one to four kilo-herz.

8.2.1 Field Chopper

Basic function of this chopper is almost identical to that of armanture chopper but with smaller current capacity. This chopper has internal feedback circuit to stabilize the output voltage at specified value regardless of input (battery) voltage. The regulator controller section was designed based on National Semiconductor's regulating pulse width modulator IC LM3524.

8.3 Computer (VPSC) Modulated Automatic Transmission and Clutch

In order to achieve efficient and effective regenerative braking, the electric motor speed has to be

kept higher than critical value (approximately 600 rpm even with regeneration chopper). It was primarily this objective that necessitated an automatic transmission shifting schedule modulation. The VPSC overrides throttle position input to the transmission in order to select lowest possible gear when regenerative braking is desired. However, the hydraulic circuit inside of the transmission does not necessarily perform precise shifting. Sometimes it shifts up to higher gear too early when the driver whichs maximum acceleration. Therefore, by VPSC, it was made possible to specify exactly at what speed to shift.

Although this hybrid vehicle was designed to operate with electric motor only at low speed, it is desirable to be able to start with the heat engine when electric motor fails or maximum acceleration is desired. Therefore the clutch modulation system was developed which is again controlled by VPSC. Hardware of this modulator is only one hydraulic cylinder and two valves which actuate the clutch. With a little sophisticated software in the VPSC the clutch engages smoothly as if it was modulated by an experienced human driver. The beauty of this modulator lies in the software of the computer which, utilizing the three informations (engine and transmission speed, clutch or hydraulic actuator pressure and requested torque) modulates the oil pressure of the hydraulic cylinder by varying duty cycle of a small solenoid valve.

8.4 The Vehicle Propulsion System Controller Program

In order to reduce the time for development, this program was written in FORTRAN language and tested extensively on IBM Personal Computer. The reason for using small IBM computer is the CPU (central processing unit) selected for VPSC computer was Motrolla 8088, which is also used in IBM-PC, therefore any program written or run on IBM-PC operates as well on VPSC computer provided that it is translated into machine language.

The role of this software is to send out commands to several devices achieving optimum, economical, smooth and safe operation of the power system.

The major parameters controlled by VPSC are:

1) Motor armature voltage
   Motor field voltage

2) Heat engine throttle valve opening

   Namely the power settings of the two power sources.

3) Clutch actuator pressure

Only these three parameters are modulated and others are simply On-Off controlled. (e.g. Transmission shifting schedule overrider, field reverser, etc.)

The way this VPSC works is similar to electronic fuel injection system in some manners. Both systems collect necessary information from the sensors and according to a given formula, tables or algorithm, determines the required parameter(s). Actually the program loops forever as long as power is on and each cycle is performed within 1/30 to 1/100 of a second. Hence it looks like it is controlling continuously and responds to input immediately. The major difference of the two systems is, from software point of view, number of parameters to be handled and not the function of the system. Certainly VPSC is larger and more complicated than EFI system, however the knowhow and the techniques developed for EFI systems were completely applicable to VPSC.

9. ENERGY CONSUMPTION ESTIMATES

9.1 Computer Simulations

As stated in section 4.5.4.1, and described in Appendix D the HYVEC program was used to aid in the selection of the most suitable drive train configuration from the candidates under consideration.

As the study proceeded it became apparent that frequent simulations of various elements of the propulsion system would be required and rather than run same on the expensive, remote and busy computer at the General Electric Company the Transportation Development Centre made available to the contractor a smaller, but equally suitable, computer for which the HVSP software was created and which is contained in Appendix G.

9.2 Simulation Comparisons

9.2.1 Fossil Fuel

Fossil fuel consumption on the EPA urban driving cycle according to the Preliminary Vehicle Design Specification (Sect. 3.4.7), the manufacturer's standard for the gasoline powered vehicle and the HYVEC and HVSP design simulations are shown on Figure 9.1.

Both the HYVEC and the HVSP simulations meet or exceed the acceptable design standards the slight variation between the two being due primarily to the somewhat higher GVW of the HVSP simulation vehicle.

It is of interest to note (as shown on Figure 9.1) that projected fossil fuel saving remains fairly constant at about 4 to 5 litres/day as long as the vehicle travels more than 70 km per day. Out to approximately 70 km per day the vehicle's propulsion energy is being supplied in part from the battery pack but after that distance the state of charge of the battery pack has been reduced to about 20% and the hybrid vehicle is operating essentially as a gasoline propelled vehicle but with regenerative braking. Since the hybrid vehicle is heavier than the standard T-115 one might assume that, after battery energy depletion, it would require more fossil fuel. This is not so however since the energy recovered through its regenerative braking capability approximately compensates for the extra fuel required due to weight increase.

9.2.2 Electrical Energy

HYVEC electrical energy consumption simulations as well as a description of the hypothesis and techniques used are described in Appendix I.

A summary of the HVSP electric energy simulations, which are based on the above, together with the vehicle design specification criteria are plotted in Figure 9.2.

As indicated the electrical energy consumption projected for the T-115 Parallel System hybrid vehicle comes well within the design requirements.

9.3 Total Projected Energy Consumption

Lines #7 and #8 of Figure 10-2 in Section 10 are based on the simulations reported in this section and project the comparative energy consumption on an annual basis of the standard gasoline powered T-115 and the hybrid conversion of the same vehicle. The projections are made on the basis of daily travel distances of 40 km, 80 km and 120 km using 260 working days per year.

The gasoline saving potential of the hybrid vehicle appears significant ranging from about 800 litres per annum (an 80% saving) when the vehicle is driven 40 km per day to 1300 litres per annum (a 43% saving) when driven 120 km per day.

Fuel cost savings (gasoline plus electricity) when calculated at 1984 average prices but not including battery amortization are also significant ranging from as much as 60% down to 33%. However when battery cost is included total fuel cost of the hybrid exceeds that of the standard vehicle the incremental increase diminishing as the distance travelled increases.

Figure 9.1

HYVEC and HVSP Fosil Fuel Consumption Simulations

EPA Urban Cycle
20C

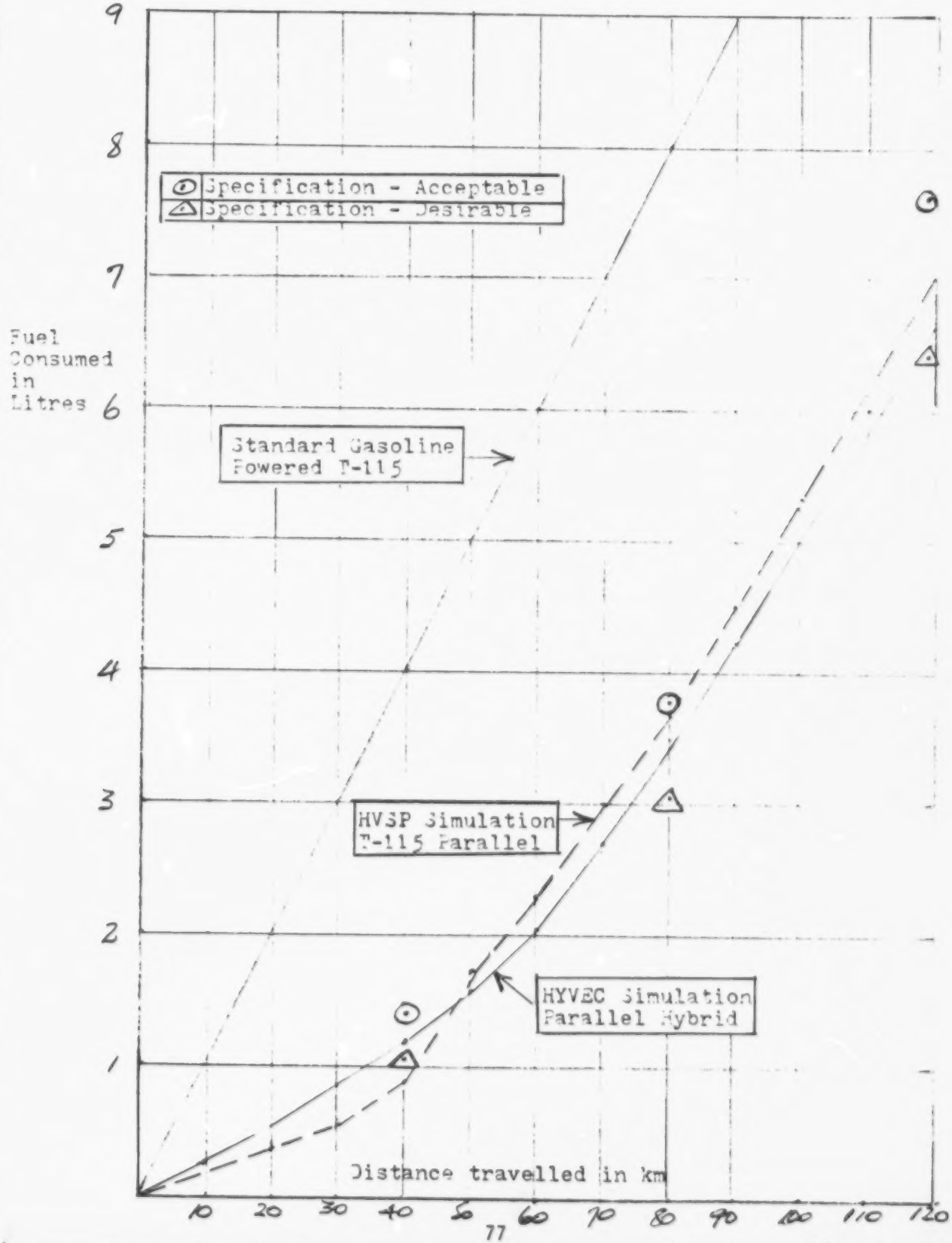
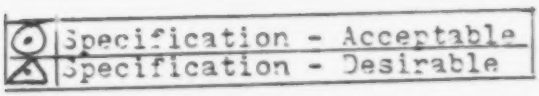
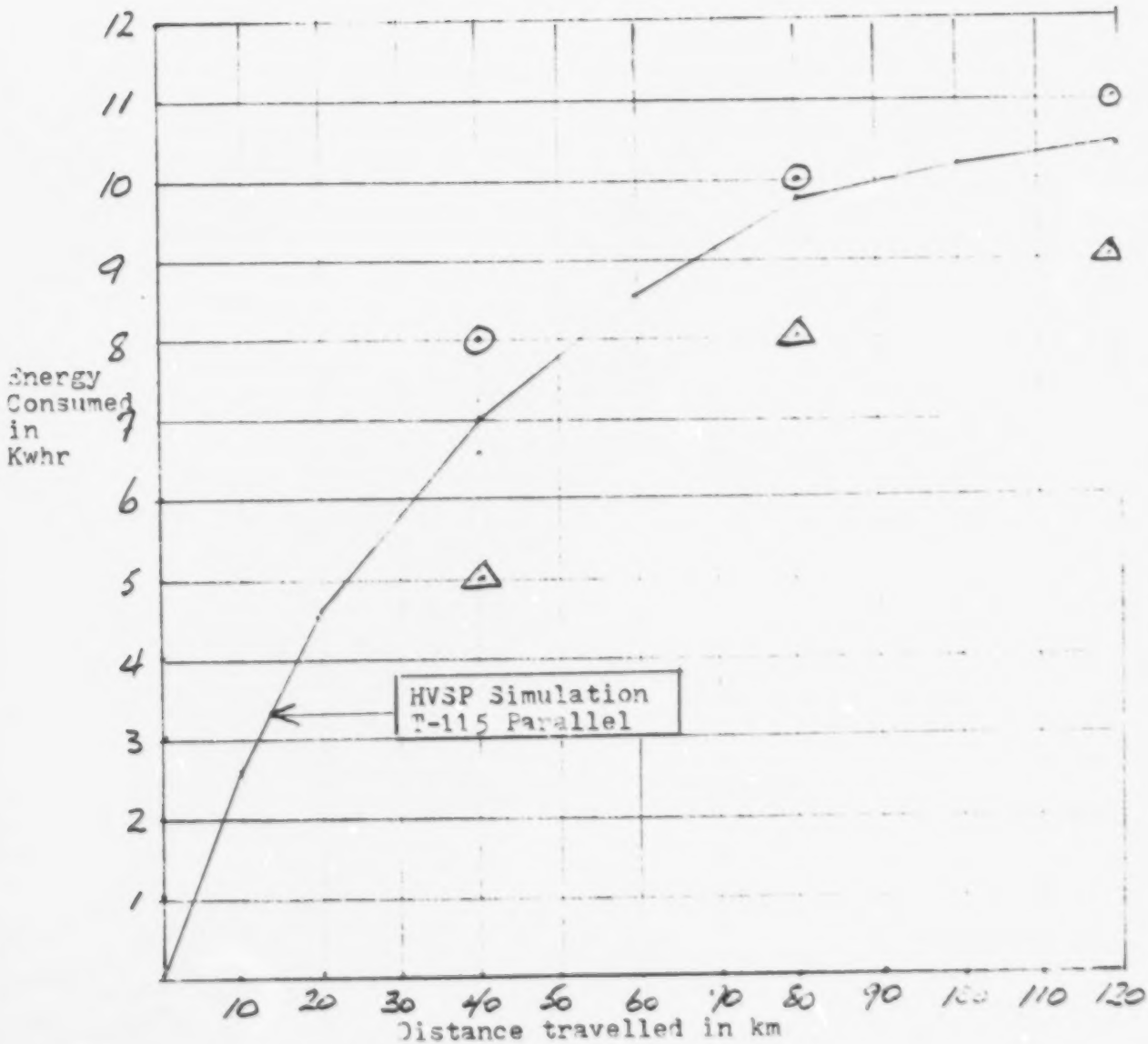


FIGURE 4-2

HVSP Simulation
Electric Energy Consumption

EPA Urban Cycle
20C





10. COSTS AND ECONOMIC FACTORS

10.1 Background

The primary purpose of the hybrid vehicle is to reduce Canada's dependence on oil by providing a cost effective alternative propulsion system which makes use of low cost wall plug electricity as a principal energy source.

To be attractive to the user the hybrid must provide a performance which approximates that of the vehicle which it will replace at an ownership cost which does not exceed that of the conventional vehicle.

The hybrid propulsion system is more complex than the regular heat engine system and contains more components, it will however, use less high cost hydro carbon fuel. The saving in fuel costs must outweigh the additional ownership costs arising from the higher initial capital outlay and higher maintenance costs if the vehicle is to achieve the necessary market penetration to provide an economical production level.

10.2 Production Volume

The T-115 van on which hybrid concept is based began production in late 1983 and the Chrysler Corporation is planning a production of 175,000 units in the 1985 model year in a facility designed to produce a maximum of 250,000 units per year. These figures indicate the volume which is required to reduce unit costs to a competitive level. The hybrid propulsion system represents a radically new approach and it is unlikely that consumer acceptance will reach the levels currently achieved by conventional vehicles for many years. For the vehicle to be introduced successfully it should be possible to produce it economically at rates of several hundreds of vehicles per year for the first year or two of production and to increase to several thousands as it gains consumer acceptance. The volume at which significant production cost breaks occur will vary for the different components of the propulsion system; it is unlikely however that any major reduction in the cost of major components or conversion labour will be achieved up to 500 units per year.

10.3 Cost Factors

Life cycle costs are made up from the capital cost of the equipment plus the direct operating costs over the life of the vehicle. In the case of vehicles making use of battery stored electrical energy the battery may be considered either as a capital item or as expendable in the same way as fuel and forming part of the direct operating costs. For the purpose of the present investigation the

batteries will be treated as expendable and costed at $2.40 per discharge cycle - i.e. $1200 per pack - 500 cycles. Lead acid batteries produced in 1984 and subjected to careful maintenance programs are capable of 400 plus cycles and a 500 cycle capability within the time frame of vehicle development and introduction is considered reasonable.

10.4 Capital Costs and Equipment Life

The list price of the T115 van which will be used as the basis for conversion is estimated at $11,500 including Federal Sales Tax. It is unlikely that, at a production of 500 vehicles per year for the first year or two of production, any significant discount will be obtained or that the manufacturer will be willing to provide anything other than complete vehicles to the convertor. There will be some recovery of cost from the new components removed from the vehicle during the conversion process and this will help to reduce the overall costs somewhat. As production volume increases the manufacturer may be expected to discount the price of the vehicle to the ocnvertor and to provide a basic chassis less the components which the convertor removes. This, in addition to the savings occuring from mass production of the major added components will lead to a significant reduction in the selling price of the hybrid vehicle. If the vehicle manufacturer undertakes the production of the hybrid vehicle further reductions in the selling price arising principally from the lower cost of the basic chassis may be expected.

Figure 10.1 shows the anticipated cost breakdown for production of 500 units per year and 20,000 units per year by a major convertor. It is to be noted that research and development, design and tooling relative to some of the special componentry for the hybrid vehicle (i.e. transmission, clutching and vehicle control systems) will require major capital expenditures as will market testing, evaluation and introduction. These costs have not been reflected in Figure 10.2.

10.5 Operating Cost Elements

Estimated comparable annual operating costs of a standard gasoline powered T-115 van, a hybrid powered T-115 produced in quantities of 500 per annum and the same hybrid produced in quantities of 20,000 per annum are tabulated in Figure 10.2.

Fuel prices (gasoline and electricity) are based on 1984 averages for Canada. General vehicle maintenance cost of $0.07 per km for the gasoline powered vehicle is based on the average cost used by fleet operators for similar sized vehicles. Because of the more complex control system and the use of dual power sources maintenance cost per km

for the hybrid vehicle is assumed to be 25% to 30% higher.

Battery cost, as per section 10.3 is charged at $2.40 per discharge cycle.

10.6 Operating Cost Comparison

Figure 10.2 sets forth the prime vehicle operating cost elements and the estimated fuel consumption rates as produced by the simulations described in section 9 and shows estimated annual operating costs for daily use (260 days per year) when operated for distances of 40km, 80km, and 120 km on the EPA Urban cycle. Fossil fuel consumption rates are based the EPA cycle at 20^{o}C and, as per section 5.5 would be greater at low temperatures.

Although the hybrid vehicle has the capability of reducing fossil fuel costs by from 70% to as mush as 400% dependent on the daily distance driven its operating costs are, as shown on Figure 10-2, very substantially higher than the standard gasoline powered vehicle even if produced in annual quantities of about 20,000. The main increments of the projected operating cost increase are higher capital amortization, battery cost and somewhat higher expected maintenance cost. Even if the "sticker price" of the hybrid conversion were the same as the standard gasoline powered vehicle its annual operating costs would still be considerably higher. For example comparing the 80km a day annual cost of the standard T-115 ($4,139) with the same travel distance cost for the hybrid produced in quantities of 20K per annum but at the same capital cost as the standard vehicle ($5,531 - $2,428 + $1,643 = $4,746) the hybrid still costs about 15% more per year to operate which is approximately equivalent to a 60% increase in the price of gasoline (over 1984 pump prices).

FIGURE 10.1

T115 Hybrid Conversions

Estimated Vehicle Production Cost

	Min. Conv. 500/Ann.	Large Conv. 20K+/Ann.
Base vehicle (F.S.T. in)	$ 9,800	
Less engine & ancill.	1,000	
Base vehicle excl. engine (F.S.T. in)	$ 8,800	$ 8,000
Heat engine & ancill.	1,100	700
Exhaust system mods.	150	25
Electric motor	1,500	300
Motor controller	1,500	300
Computer	250	50
Computer interface	500	50
Actuators	250	100
Sensors	200	50
Transmission mode	500	incl.)
	$ 5,950	$ 1,575
Conversion labor	1,500	700
Conversion labor - 100% mark-up	1,500	700
Parts mark-up	600	150
Base vehicle mark-up	1,000	800
	$19,350	$11,925
Profit at 15%	2,900	1,800
F.S.T. on addns.	950	350
Warranty (5%)	1,250	700
	$24,450	$14,775
Dealer mark-up at 15%	3,600	2,200
	$28,050	$16,975

Not included: R & D costs
Tooling costs
Marketing costs
Financing costs

FIGURE 10.2

ESITMATED OPERATING COST - EPA URBAN

&

FOSSIL FUEL SAVING

	STANDARD GASOLINE POWERED T115 VAN			HYBRID CONVERSION 500 UNITS PER YEAR			HYBRID CONVERSION 20K+UNITS PER YEAR		
1. Approx. unit cost (ex. batteries)	$11,500			$28,000			$17,000		
2. Estm. vehicle life - no residue	7 yrs			7 yrs			7 yrs		
3. Fuel cost-gasoline/l	$0.50			$0.50			$0.50		
-electricity/kwh	0.05			0.05			0.05		
4. Maintenance Cost/km	0.07			0.09			0.09		
5. Batt. Amort. cost **	NIL			$2.40/cycle			$2.40/cycle		
6. EPA Avg. Travel / day km	40	80	120	40	80	120	40	80	120
7. Fuel Consm. Rate									
-gas l/100 km	10	10	10	2.13	4.62	5.83	2.13	4.62	5.83
-elect kwh/km	-	-	-	0.175	0.122	0.087	0.175	0.122	0.087
8. Fuel Consm. Qty/Ann*									
-gas/l	1040	2080	3120	222	961	1819	222	961	1819
-elect/kwh	-	-	-	1820	2537	2714	1820	2537	2714
9. Annual Operating Cost									
-fuel - gasoline	$520	$1040	$1560	111	480	910	111	480	910
-fuel - electricity	-	-	-	91	127	136	91	127	136
-battery amortization	-	-	-	624	624	624	624	624	624
TOTAL	520	1040	1560	826	1231	1670	826	1231	1670
-Gen. Maintenance	728	1456	2184	936	1872	2808	936	1872	2808
-Capital Amortization	1643	1643	1643	4000	4000	4000	2428	2428	2428
TOTAL	$2891	$4139	$5387	$5762	$7103	$8478	$4190	$5531	$6906
10. Cost Incr. per annum	-	-	-	100%	72%	57%	45%	34%	28%

*Based on 260 Days/Yr.

APPENDICES

A. ONTARIO RESEARCH FOUNDATION - VEHICLE TRANSMISSION EVALUATION

B. TIRE ROLLING RESISTANCE AT LOW TEMPERATURES HEATER CAPACITY CALCUATIONS

C. HEAT ENGINE SIZING

D. HYVEC COMPUTER VEHICLE SIMULATION PROGRAM

E. EPA DRIVING SCHEDULES

F. COMPONENT SELECTION

G. HVSP HYBRID VEHICLE SIMULATION PROGRAM

H. VPSC VEHICLE PROPULSION CONTROL SYSTEM

Program Specification

" Description

" Source Code Listing

I. HYVEC DESIGN SIMULATIONS - PARALLEL VEHICLE

APPENDIX A

EXAMINATION OF HYBRID DRIVE SYSTEM

PROPOSED BY

THE ONTARIO RESEARCH FOUNDATION

1.0 BACKGROUND

1.1 Description of Proposal

ORF has proposed a transmission system for use in Hybrid Electric Drive Vehicles. The system, Figure 1, is made up of a differential gear in which drive from a heat engine is applied to one of the pinion shafts; a motor generator is coupled to the differential carrier through a gear set of approporiate ratio and the output is taken from the second pinion shaft. The motor/generator is connected to the battery pack through a controller. Brakes are fitted to the engine and motor/generator shafts.

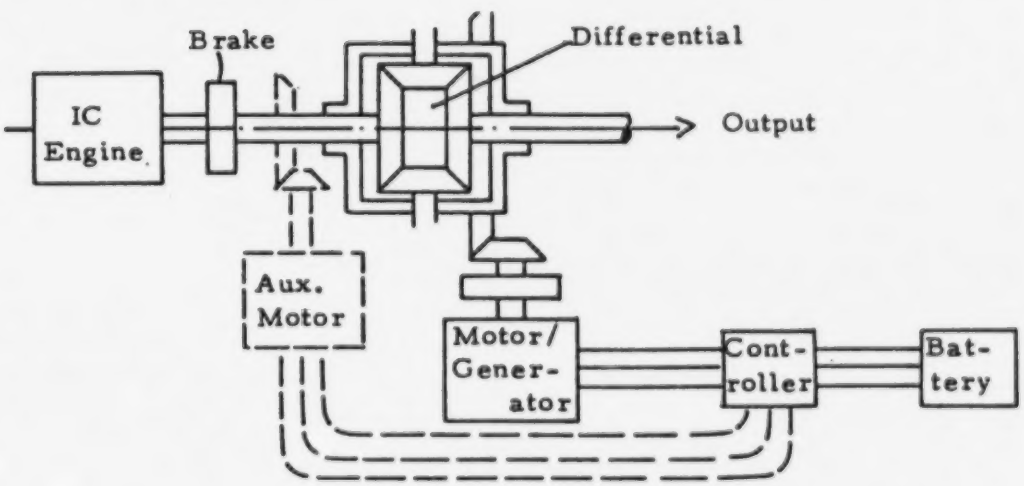


Figure 1 - ORF Proposals

1.2 Alternative Proposal

In an extension of the proposal described as "Alternative A" ORF proposes the inclusion of an auxilliary motor coupled to the input shaft through a one way clutch. The additional equipment is shown in dotted lines in Figure 1.

2.0 OPERATION

2.1 Basic Concept

When the vehicle is at rest the output pinion shaft is restrained by the motion resistance of the vehicle. With the IC engine operating the differential carrier will rotate in the same direction as the input shaft but at one half of its rotational velocity.

2.2 If the generator field is now excited an EMF will be produced and a charging current will flow into the battery. The torque required to drive the generator will oppose the rotation of the differential carrier and cause a torque to be developed in the output shaft:

If

TE = Engine Torque

T_C = Carrier Torque

TO = Output Shaft Torque

then

$$TE = \frac{TC}{2} = TO$$

2.3 As the resistance to motion of the carrier is increased the motion resistance of the vehicle will be overcome and the output shaft will rotate, leading to a reduction in the speed of the carrier. The velocity relationships are:

$$NO = \frac{NC}{2} - NE$$

where

N_O = speed of output shaft

N_E = speed of engine

N_C = speed of carrier

and if

$N_C = 0$

$N_O = -N_E$

and the output shaft will run at the same speed as the engine but in the opposite direction.

2.4 The characteristics of the generator will limit the minimum effective value of NC and it will be necessary to apply the brake on the generator shaft to bring the carrier to rest.

2.5 The motor/generator may now be operated as a motor to increase the speed of the carrier and provide an overdrive if desired.

2.6 The vehicle may be driven by either the engine or the motor by applying the brake on the non-driving shaft. No variable speed/torque drive is included in the system in these conditions.

2.7 Alternative "A"

The same basic operating principles applying to the base system apply also the Alternative "A". In this case, however, the power produced by the generator is supplied to the auxilliary motor and produces an additional input torque to the engine shaft.

3.0 LIMITATIONS

3.1 Basic System

3.1.1 Battery Capacity

For the system to function it is necessary for the battery to accept the energy dumped by the generator at current levels determined by the torque demand. Problems will obviously exist when the batteries are at or near full charge. This factor requires further investigation.

3.1.2 Torque Limits

The most serious limitation is the inability of the system to deliver output torque above the maximum engine shaft input torque. The freely rotating differential pinions ensure that the torque in the input and output shafts are equal at all speeds and under all conditions of operation. The engine input power is divided between the batteries and the output shaft in the ratio of the speeds of the generator to the output shaft. The transmission is primarily a variable speed constant torque device.

3.2 Alternative "A"

The maximum output torque which can be generated by this arrangement is limited by the maximum resistive torque which can be developed by the generator. If, in a typical case, the generator is coupled to the differential carrier by a 2:1 gear set so that it has the same rotational speed as the engine when the output shaft is stationary the torque in the output shaft will be:

$$T_O = T_G$$

where T_G = generator torque

The value of TO in this case cannot exceed the maximum torque which the motor/generator can absorb and may be less than this if the auxilliary motor and batteries cannot, together, absorb the power being produced by the motor/generator.

4.0 POWER SHUNT ARRANGEMENT

A further alternative arrangement in which the motor is coupled to the output shaft is shown in Figure 2.

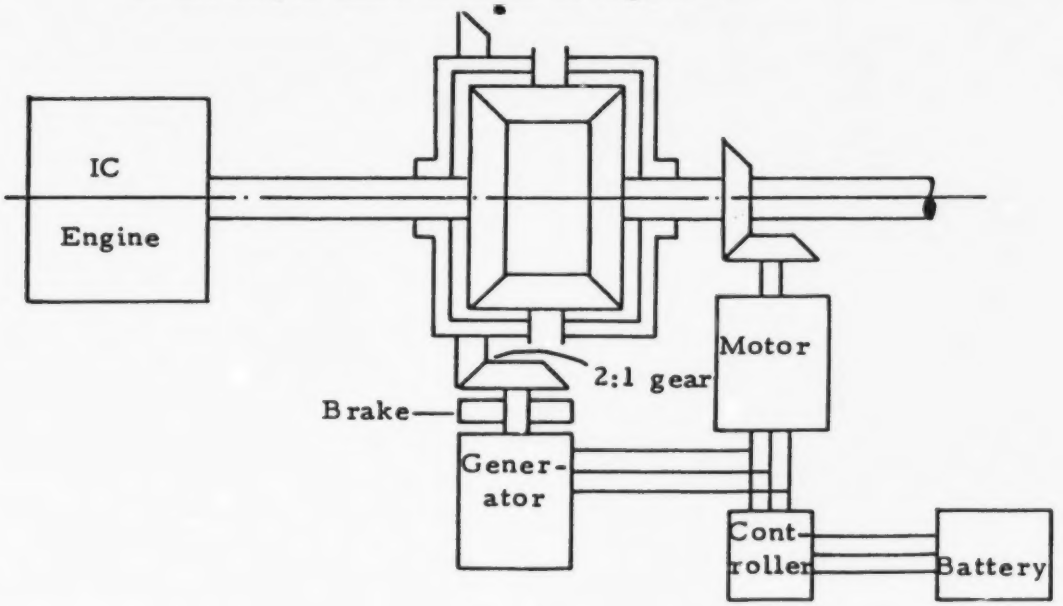


Figure 2 - Power Shunt Arrangement

In this arrangement, when the output shaft is stationary, the generator is driven at engine speed and is capable of generating its maximum current. The motor is stationary and can, for short periods, develop its maximum torque. Under these conditions the motor can develop about 4.5 times the torque which the generator will apply to the differential carrier. The torque multiplication will fall to about 1:1 when the motor speed approaches that of the generator. If the generator is connected to the differential carrier so that:

$$T_C = 2T_A$$

the maximum torque multiplication at zero output speed may be calculated thus:

$$TE = \frac{TC}{2} = TG$$

$$T_M = 4.5\,T_G$$

$$TO = TM + \frac{TC}{2}$$

$$= 4.5\,T_G + T_G$$

$$= 5.5\,T_G$$

$$= 5.5\,T_M$$

4.2 This arrangement clearly overcomes the torque limitations inherent in both the original proposals. It also offers the following potential advantages:

- A continuously variable gear ratio is available from zero output speed to the point at which the generator speed falls to the point where it no longer develops resistive torque sufficient to maintain system balance.
- Only one clutch is essential.
- The IC engine may be operated at its most economical point at all times (provided that a suitable control strategy can be developed).
- The electric motor may be used as the sole source of power or to assist the IC engine on a full or part time basis.

4.3 The obvious drawbacks are:

- An additional major electrical component is required leading to increased cost and weight.
- No transmission of this type is available and development will be required.
- The development of a control strategy which will ensure maximum efficiency and satisfactory battery/generator/ motor interfaces may prove difficult.

5.0 CONCLUSION

Preliminary investigation of the ORF proposals indicates that, as presented, they do not offer significant advantages over other transmissions. With a minor variation of Alternative A to provide a power shunt arrangement, however, significant potential advantages over other types of transmissions appear.

Appendix B

TIRE ROLLING RESISTANCE AT LOW TEMPERATURES

1.0 Introduction

1.1 The motion resistances developed in an automobile tire arise principally from hysteresis losses as the tire is deflected during rolling motion. The resistances are affected by the load, tire pressure and the temperature of the tire carcass. The effects of low temperatures on the rolling resistance of a tire at a given load and inflation pressure are of interest in the design of any vehicle which will be required to operate in Canadian winter conditions.

1.2 Reference 1 provides information on the effect of ambient temperatures on the rolling resistance of P195/75R14 steel radial tires of various tread configurations. This tire is one of those being considered for the hybrid vehicle and data relating to the highway tread design is used in these notes.

2.0 Analysis of Data

2.1 Figures 1 and 2 (2 & 3 from reference) illustrate the effect of ambient temperature on tire motion resistance and the rapid warm-up which takes place when the tire is operated at 80 Km/hr. While the 15 minute operation provided by the test procedure is not enough for the tire temperatures to have stabilized, a very substantial levelling of the time/temperature curve has taken place and they will be considered as stable for the pruposes of these notes.

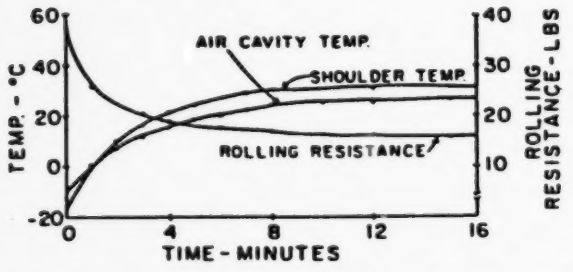


Fig. 2 - Time dependence of tire temperature and rolling resistance. P195/75R14 5 rib highway design. 1213 lb (5400 N), 30 psi (270 kPa) at 20°C, 50 mph (80 kph) -20°C ambient temperature

Figure 1

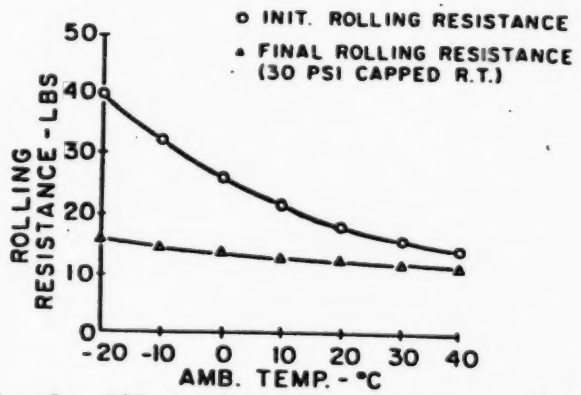


Fig. 3 - Effect of ambient temperature on initial and final tire rolling resistance. P195/75R14 5 rib highway design. 1213 lb (5400 N), 30 psi (207 kPa) at 20°C, 50 mph (80 kph)

Figure 2

2.2 It will be noted from Figure 2 that the final tire temperature and hence the motion resistance depends on the ambient temperature. At an ambient temperatue of -20oC the final motion resistance at 80 Km/hr is about 16 lb compared with 12 lb at +20PoC. At -30oC, which is a reasonable lower design ambient temperature for the hybrid, the final rolling resistance is estimated to be 50% higher than that at +20oF at which rolling resistance figures are normally calculated.

2.3 When the hybrid is employed in the urban environment average speeds are likely to be of the order of 32 Km/hr (20 mph). At this speed the rate of warm up of the tire will be slower and the final rolling resistance higher than that at 80 Km/hr (50 mph) estimated above. From the data presented (?) it is estimated that the tire carcass will attain a temperature of about 0oC when the vehicle is operated at 32 Km/hr in ambient temperatures of -30oC and the rolling resistance will be about 80% higher than that experienced at +20oC.

2.4 The effects of low temperatures on the rolling resistance may be summarized thus:

- the power required to overcome tire rolling resistance at -30oC when the vehicle is operated on the highway at speeds of 80 Km/hr will be about 50% greater than that required at +20oC

- the power required to overcome tire rolling resistance at -30oC when the vehicle is operated in the urban environment at an average speed of 32 Km/hr is about 90% greater than that required at +20oC

Reference 1. SAE Paper 800090 - Effect of Ambient Temperatures on Radial Tire Rolling Resistance, M.L.Jannssen and G.L.Hall

HEATER CAPACITY

1.0 Conditions

Ambient Temperature	$-20\ ^{o}F$
Required Compartment Temperature	$+80\ ^{o}F$
Heater Outlet Temperature	$110\ ^{o}F$
Fresh Air Requirement	100%
Fresh Air Volume	300 cfm
Inlet Water Temperature	$170\ ^{o}F$

$$DT = 170 - (-20)$$
$$= 190\ ^{o}F$$

$$\text{Heater Capacity} = 210 \times 190 \text{ BTU/h}$$
$$= 38{,}000 \text{ BTU/h}$$

2.0 The above applies to truck cabs (Ref. 1) and probably represents the minimal requirement for a utility vehicle.

3.0 For a flow of 300 cfm from the heater the temperature rise in the heater will be

$$\frac{38{,}000}{300 \times SpG110 \times Dcp \times 60}$$

$$= \frac{38{,}000}{300 \times 0.0695 \times 0.238 \times 60}$$

$$= 127\ ^{o}F$$

4.0 Heater output at $0\ ^{o}F = 210 \times 170$

$$= 34{,}000$$

Reference 1. SAE Paper 750400. Cab Condition - Heating and Cooling - Heavy Duty Truck and Off Highway Equipment

APPENDIX C

ENGINE SIZING

1. Power Requirements

The preliminary investigation of power requirements in Section 5.1.2 indicates that 35.9 HP is required to propell the vehicle at 105 kmh on a smooth level road. Figure 1 illustrates the variation of the horsepower required to overcome the various resistances with road speed. Tire rolling resistance is the principal factor up to about 59 kmh when air resistance becomes dominant and rapidly increases with speed until at 100 kmh it represents about 50% of the total horsepower required. The aerodynamic drag coefficient of 0.48 which was selected for the preliminary examination is a conservation estimate based on a relatively simple vehicle design: it may prove possible to reduce this to about 0.40 by careful design and Figure C2 shows the effect of this on the total horsepower required. The reduction of 0.3 HP or 2.5 HP at 100 kmh are insufficient to affect the engine selection. It is to be noted that the power requirements have been estimated for operation of the vehicle at 21 ^{o}C; increased tire resistance and higher power train losses will increase the power requirements by about 20% for operation at -29 ^{o}C.

2. Required Engine Characterisitics

The engine should be capable of propelling the vehicle at speeds up to its maximum with low fuel consumption, have minimum practicable weight and bulk and have alife comparable to that of engines installed in similar vehicles. It is highly desirable that the engine be of a type already marketed in Canada and for which a dealer servicing organization is in being.

3. The vehicle may be expected to be driven at speeds close to the acceptable and/or desirable maximum and may sustain speeds of 100 kmh for considerable periods when operating on suburban highways., In the interests of ensuring reasonable engine life and reducing vehicle noise levels it should be capable of producing the power required when operated at wide open throttle and 70% of the4 speed for maximum power.

4. Figure C3 shows the estimated power and torque curves for the Suzuki 0.97 litre four cylinder engine. Approximate fuel consumption curves have been sketched. This engine is rated at 45HP (SAE net) at 5500 rpm and may be expected to develop about 37 HP at 3750 rpm. An engine at half life will have developed some wear and suffered a loss of tune leading to a reduction of about 10% in the net horsepower developed.

5. Figure 1 indicates that 30 HP is required to propel the proposed vehicle at 100 kmh. The Suzuki 0.97 litre engine will provide 34 HP or more at 70% of its rated speed over most of its useful life.

The approximate fuel consumption map in Figure C3 shows that at a road speed of 100 kmh (3750 rpm engine speed) the fuel consumption will lie in the 0.5 lb/BPH hour range.

6. Conclusion

The engine, when new, should develop about 40 HP at 70% of its maximum rated speed in order to propell the vehicle at the desired maximum speed. The Suzuki 0.97 litre engine comes close to meeting this requirement.

Figure 1 Level Road Power Requirement

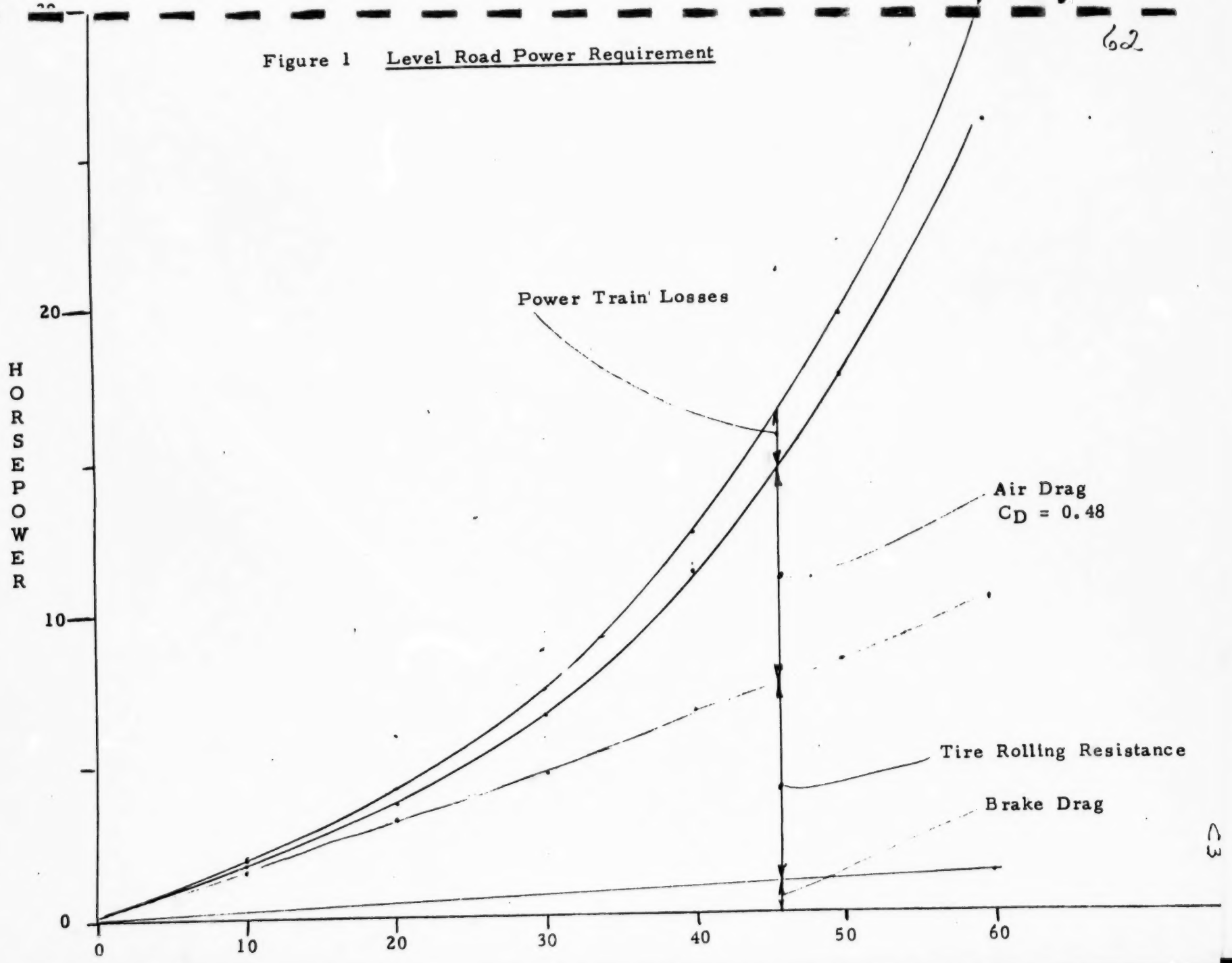


Figure C2 Effect of Reducing Drag Coefficient on Level Road Horsepower

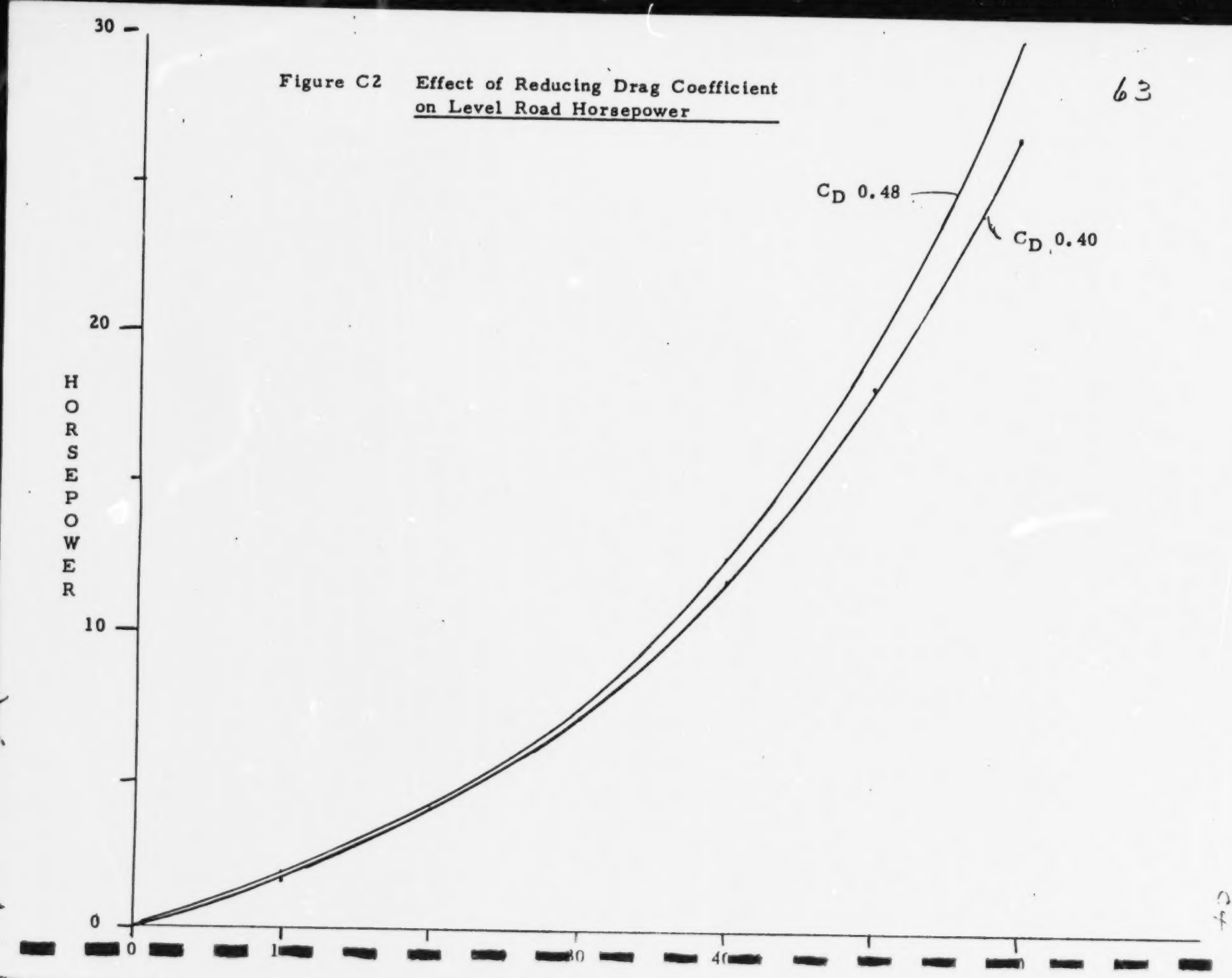
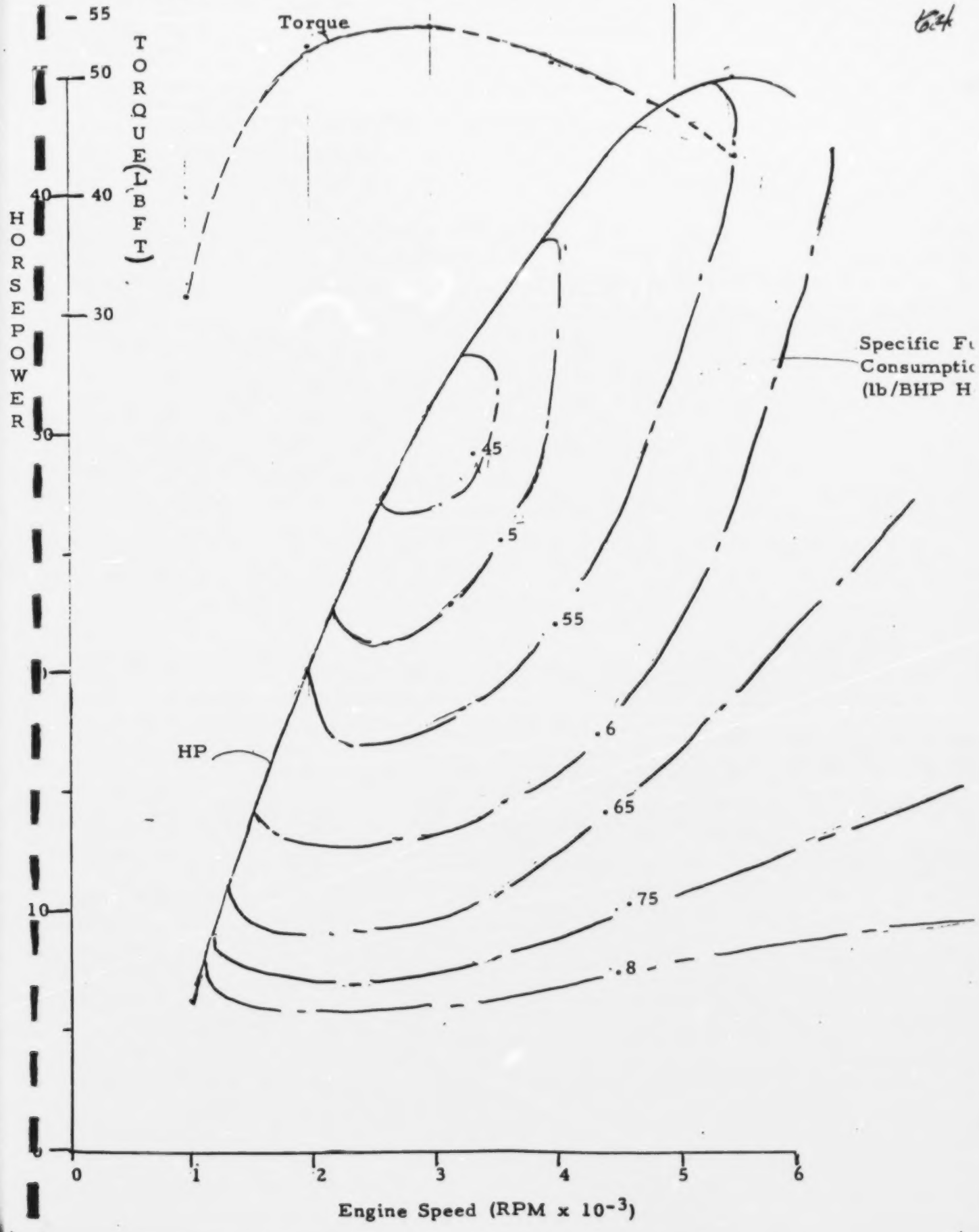


Figure C3 Estimated WOT Characteristics 45 HP Carburetted Engine



 Appendix D

The computer program (HYVEC) was developed to simulate second-by-second operation of electric and hybrid vehicles over urban and highway driving cycles. A complete listing of the program is given in General Electric Report, SRD-79-134/5, October 1979. A schematic of the HYVEC calculation procedure is shown in Figure 12. As indicated in the figure, the calculation is performed starting at the wheels and working component-to-component through the power train until the fuel and/or electricity needed to drive the vehicle for each increment of time is determined.

Detailed models based on experimental data and analysis are used for each of the power train components. For the electric drive system, motor voltage and current are determined and used as inputs to a battery model which describes the battery in terms of terminal voltage as a function of battery current and state-of-charge (Figure 13). Battery state-of-charge is expressed as the ratio of the AH-used to the cell AH capacity at the time-averaged discharge current. All the electrical power train components are modeled using scaling factors which permit the component sizes (ratings) to be changed without altering the basic inputs to the program. The electric motor is described in terms of the continuous rated power, base speed, and nominal rated voltage and flux. The battery is described in terms of cell AH-rating at the C/3 rate and the number of cells in each battery module (i.e., nominal battery voltage).

The mechanical driveline components, the heat engine and transmission, are modeled in a conventional manner. The heat engine is described by its maximum power and rpm. Fuel consumption and emissions characteristics are input as maps of bsfc and bsem (brake specific emissions – HC, CO, NO_x, particulates) as functions of percent speed and percent of the maximum power at that speed fraction. The multispeed gearbox transmissions are described in terms of the gear ratio and efficiency in the various gears and the pumping losses if the gearbox is hydraulically shifted. The continuously variable transmission (CVT) is described in terms of the maximum reduction speed ratio and the maximum overdrive speed ratio. Friction and pumping losses are combined into a single, speed-dependent loss term for the CVT.

The control strategy for operating the hybrid power train is described in HYVEC by a series of statements which specify under what conditions the engine is on, what fraction of the power required is supplied by the electric motor, when the gearbox should be shifted or the battery charged, how the accessory loads should be met, and so forth. Development of the control strategy for a hybrid vehicle is a key part of the system design, and the HYVEC program is an important tool in that development. The details of the control strategy used in the GE Near-Term Hybrid Vehicle are discussed in General Electric Report SRD-79-134/6 October 1979.

The HYVEC program can also be used to calculate the maximum effort acceleration performance of electric and hybrid vehicles. In those calcula-

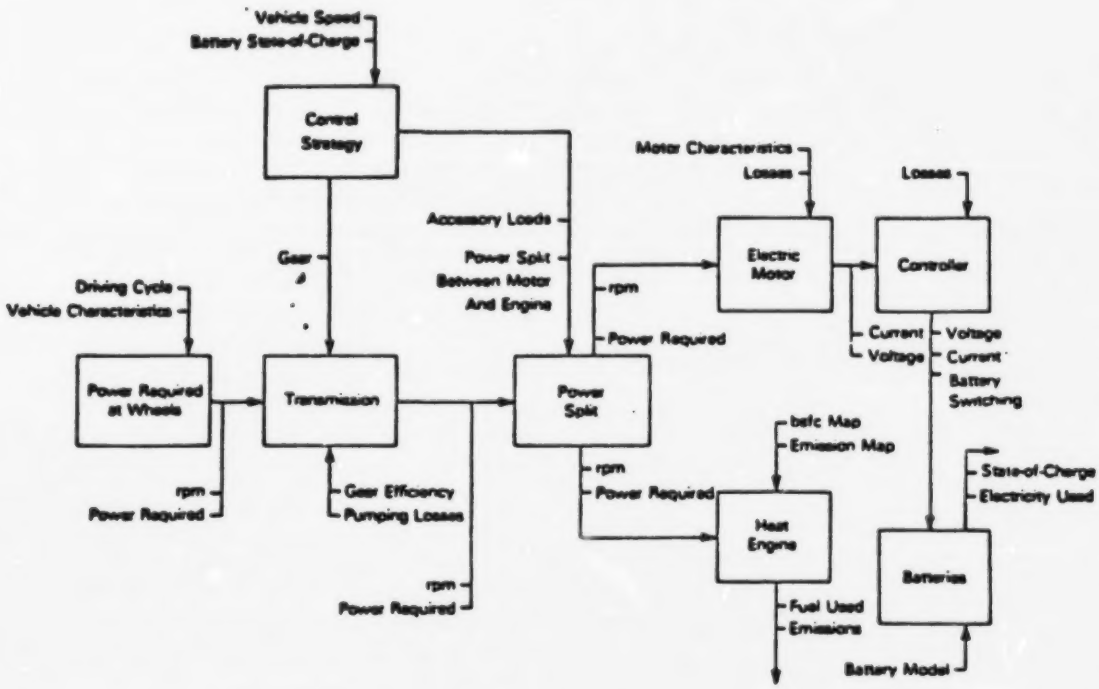


Figure 12. Schematic of the Hybrid Vehicle Simulation Calcula[illegible] (HYVEC).

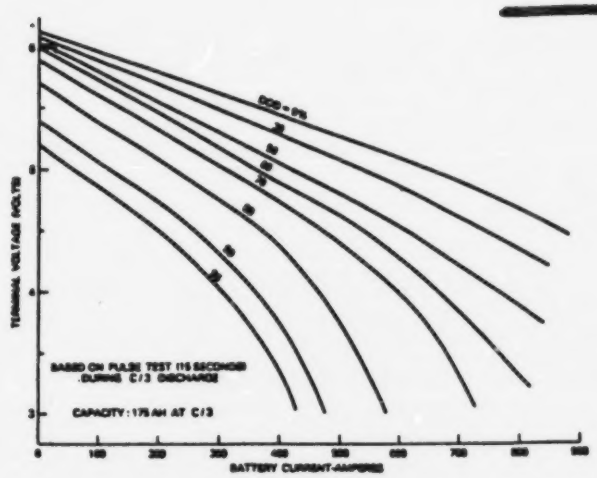


Figure 13. Current-Voltage Characteristics of the ETV-1 Lead-Acid Battery.

tions, the electric motor and heat engine are operated at the maximum power (or torque) attainable from them at each vehicle speed. The gear shifting strategy is such that the motor and engine are permitted to operate much nearer their maximum rpm than in usual driving. Particularly for the heat engine, this increases the power available at moderate vehicle speeds. The maximum power attainable from the electric drive system depends on the state-of-charge of the battery. As the battery charge is depleted, the voltage drop of the battery increases at high currents and the maximum power the battery can provide becomes smaller. Maximum effort acceleration calculations at specified levels of battery state-of-charge can be made with HYVEC.

The HYVEC program has been used to project the performance of both the GE Near-Term Electric (ETV-1) and the Hybrid (HTV) Vehicles. The physical and power train characteristics of those vehicles are given in Table 2. The range on the SAE J227a D cycle and the acceleration of the ETV-1 as a function of battery state-of-charge are shown in Figures 14 and 15. The predicted maximum range is 69 miles. The acceleration times for 0-30 mph are 9.5 and 10.7 seconds for battery states-of-charge of 100% and 20%, respectively. The urban fuel economy and the acceleration characteristics of the HTV are given in Figures 16 and 17. The control strategy of the HTV is to use battery-stored electricity whenever it is available and the electric drive system can meet the power demand. The battery is discharged to a depth-of-discharge of 80% at which time the electric drive system is only used to start the vehicle from rest (up to a speed of 12 mph) and to meet peak power demands which can not be met by the heat engine alone. The battery state-of-charge is maintained between 20 and 30% by using the heat engine to charge the battery as required. The strong dependence of the hybrid vehicle fuel economy on distance traveled since the battery was last charged from the wall-plug is shown in Figure 16. Hence, as discussed in Burke, Smith, February 1981, the annual average fuel economy of the hybrid vehicle depends markedly on the use-pattern of the vehicle. The acceleration results shown in Figure 17 indicate that the 0 to 55 mph acceleration times of the HTV are comparable to those of a conventional ICE vehicle being 14 and 17 seconds for battery states-of-charge of 100% and 20%, respectively.

The HYVEC program has also been used to predict the performance of electric and hybrid vehicles using more advanced components than those utilized in the ETV-1 and HTV. Results using nickel-zinc batteries and diesel engines are given in Figures 18 and 19. As would be expected, use of the advanced components would improve the performance and thus the attractiveness of both types of vehicle.

TRANSIENT VEHICLE OPERATION

Gearshifting Transients (VTAP)

The HYVEC computer program assumes quasi-steady operation of the vehicle with time steps of one second. Transients in the electrical propulsion system, which have characteristic time constants of 200 ms or less, were thus neglected. In HYVEC, it is assumed that gear changing occurs smoothly within the one second time step and that no transients in motor armature current result. The VTAP computer program focuses on the armature current transients occurring during gear changing. These transients can have important effects on vehicle driveability and on the design and adjustments of some of the propulsion system components (e.g., transmission shift times, motor field response times).

During gear changing, a relatively large change (20% to 30%) in motor speed occurs in a short time (400 to 800 ms). The motor field current must respond faster than the transmission shifting in order to control the motor armature current. The VTAP program was developed to study this problem and to determine optimum values for the electric motor field time constant and the transmission shifting time. The present study treated an automatically shifted gear box (without torque converter) so that power to the vehicle was not interrupted during shifting.

A block diagram of the VTAP program is shown in Figure 20 and consists of three major elements: (1) the vehicle subsystem which includes the road load model and transmission (2) the electric motor with feedback control, and (3) the brake/accelerator command model. The desired command acceleration as a function of time, the initial vehicle speed, and the grade are inputs to the program. The required rotational speed and torque at the wheels for the specified vehicle speed and acceleration are computed from the road load model. The corresponding quasi-steady state operating conditions of the power train are used as the command values which would result from the operator brake and accelerator pedal signals in the actual vehicle.

Table 2

PHYSICAL AND POWER TRAIN CHARACTERISTICS OF THE ETV-1 AND HTV

	ETV-1	HTV
Physical		
Inertia Weight (Kg)	1660	2023
C_DA (m^2)	0.58	0.86
Rolling Resistance (%)	1.0	1.1
Power Train		
Type	Electric	Parallel Hybrid
Electric Motor		
Continuous (kW)	15	17
Maximum (kW)	30	34
Control	Armature and Field Chopper	Battery Switching and Field Chopper
Heat Engine		
Maximum (kW)	-	55
Batteries		
Type	Lead-Acid	Lead-Acid
Voltage	18 6 V Modules	10 12 V Modules
Weight (kg)	490	364
Cell Size (AH at C/3)	175	106
Transmission		
Gear Ratios	1.0	2.84/1.6/1.0
Final Drive Ratio	5.68	2.84

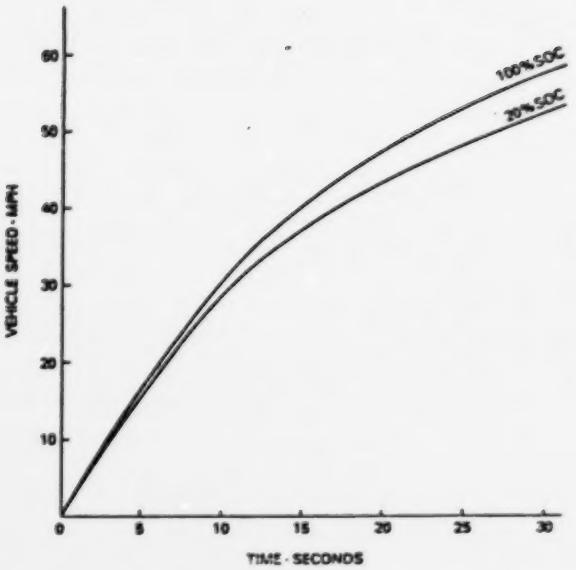


Figure 15. Computer Simulation of the Acceleration Performance of the ETV-1.

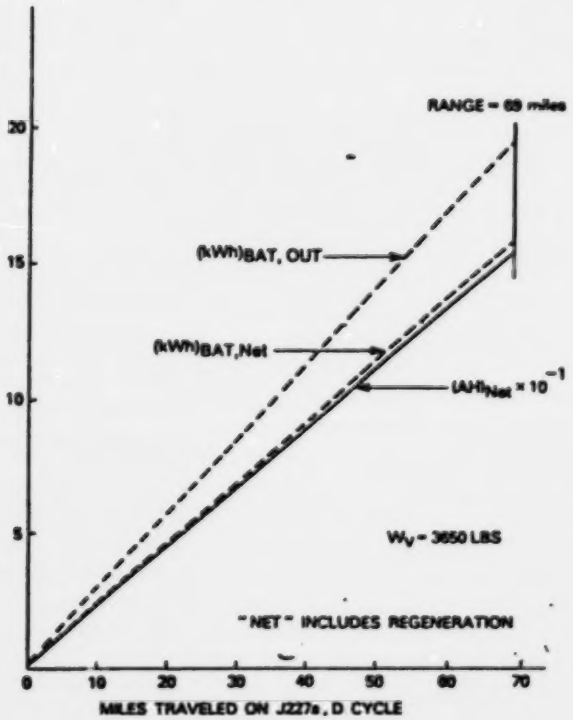


Figure 14. Computer Simulation of Range of the ETV-1.

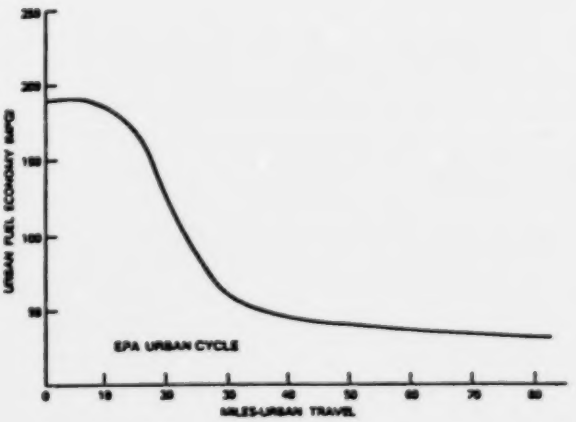


Figure 16. Fuel Economy of the Hybrid Vehicle (HTV) in Urban Driving.

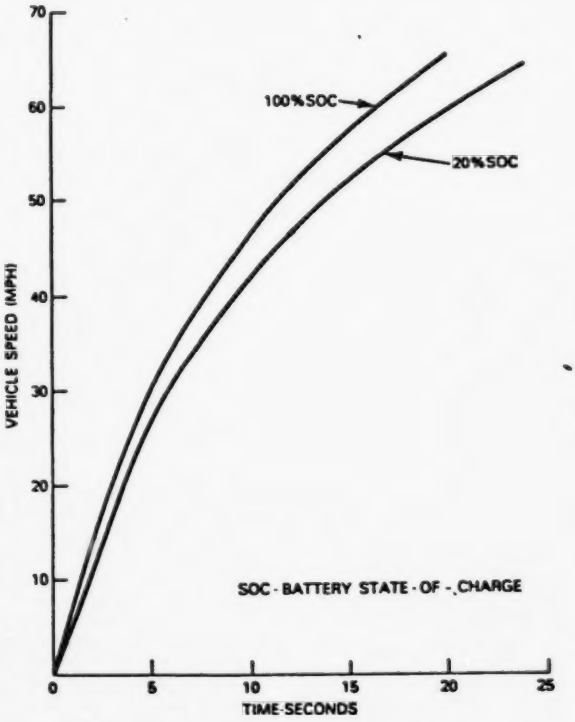


Figure 17. Acceleration Characteristics of the Hybrid Vehicle (HTV).

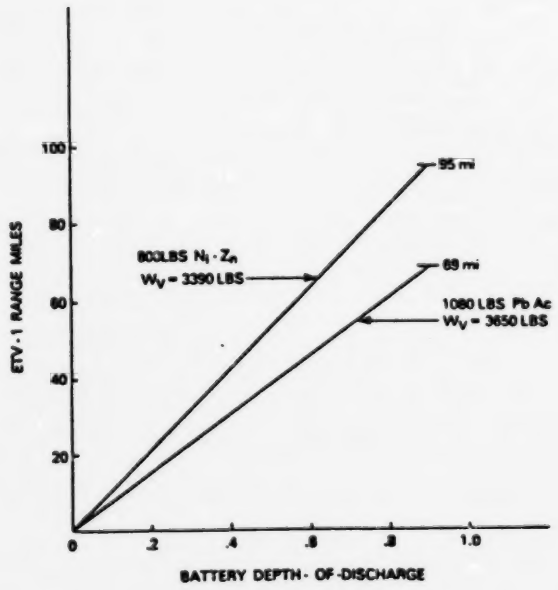


Figure 18(a). Comparison of the Range of the ETV-1 Using Lead-Acid and Ni-Zn Batteries.

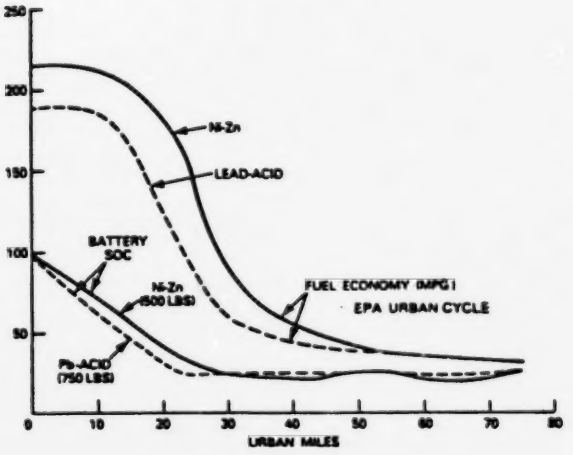


Figure 18(b). Comparison of the Fuel Economy of the Hybrid Vehicle (HTV) Using Lead-Acid and Ni-Zn Batteries.

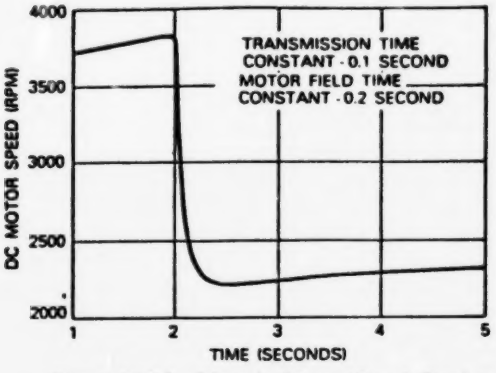


Figure 21(a). Electric Motor Speed During Gear Changing.

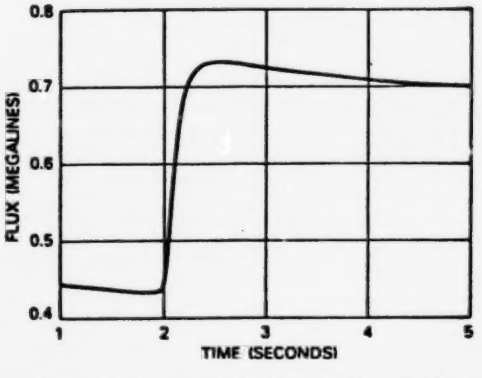


Figure 21(b). Electric Motor Flux During Gear Changing.

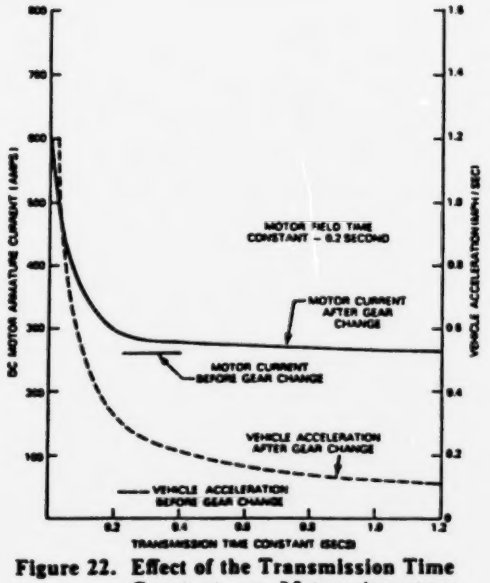

MOTOR FIELD TIME CONSTANT - 0.2 SECOND
MOTOR CURRENT AFTER GEAR CHANGE
MOTOR CURRENT BEFORE GEAR CHANGE
VEHICLE ACCELERATION AFTER GEAR CHANGE
VEHICLE ACCELERATION BEFORE GEAR CHANGE

Figure 22. Effect of the Transmission Time Constant on Motor Armature Current and Vehicle Acceleration.

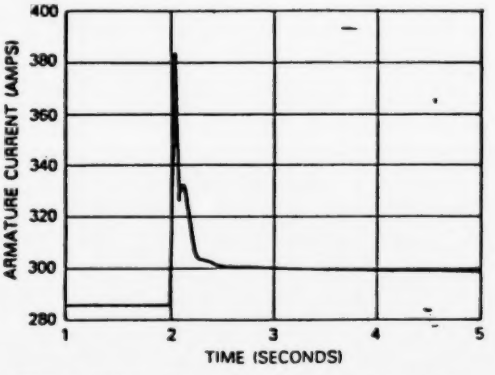


Figure 21(c). Electric Motor Armature Current During Gear Changing.

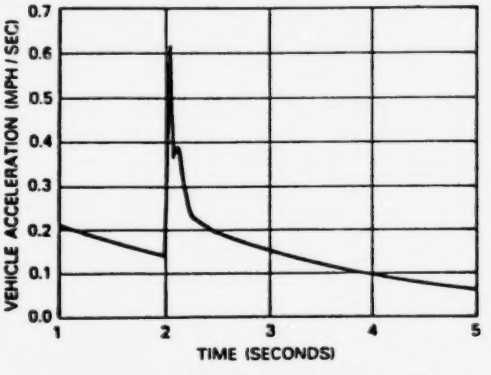


Figure 21(d). Vehicle Acceleration During Gear Changing.

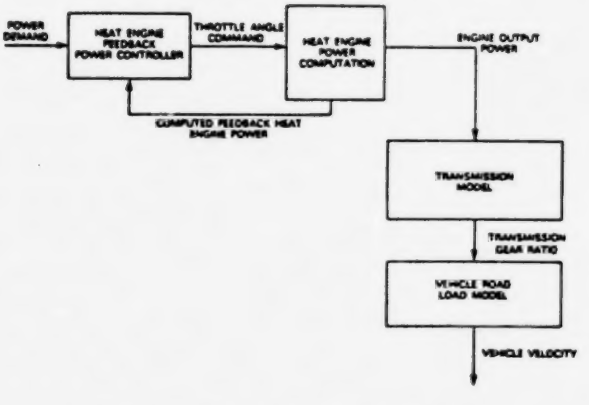


Figure 23. Schematic of Heat Engine Simulation Program (HESIM).

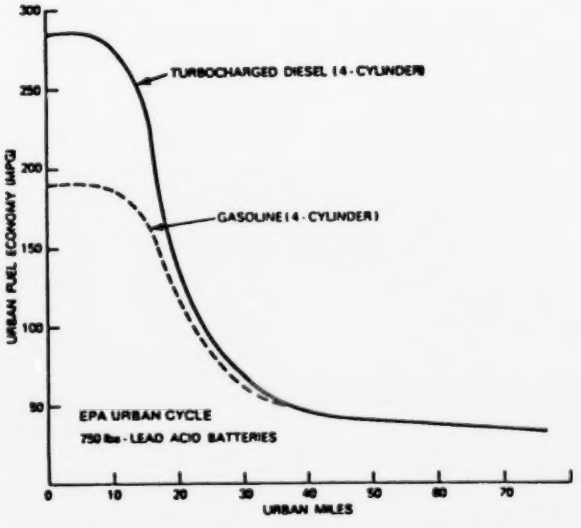


Figure 19. Comparison of Urban Fuel Economy for the Hybrid Vehicle (HTV) Using Turbo-Charged Diesel and Gasoline Engine.

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2. Burke, A.F. and Smith, G.E. (February 1981) "Impacts of Use-Pattern on the Design of Electric and Hybrid Vehicles," *SAE Paper 810265.*
3. "Near-Term Hybrid Vehicle Program – Final Report – Phase I, Appendix A, Mission Analysis and Performance Specification Studies Report," *General Electric Report, SRD-79-134/2,* October 1979.
4. "Near-Term Hybrid Vehicle Program – Final Report – Phase I, Appendix B, Computer Program Listings" (Vol II), *General Electric Report SRD-79-134/5,* October 1979.
5. Burke, A.F. and Somuah, C.B. (September 1980) "Power Train Trade-offs for Electric and Hybrid Vehicles, Convergence," 80, *International Conference on Transportation Electronics.*
6. "Near-Term Hybrid Vehicle Program – Final Report – Phase I, Appendix D, Sensitivity Analysis Report," *General Electric Report SRD-79-134/7,* October 1979.
7. "Near-Term Hybrid Vehicle Program – Final Report – Phase I, Appendix C, Preliminary Data Design Package," *General Electric Report, SRD-79-134/6,* October 1979.
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APPENDIX E

EPA DRIVING SCHEDULES

1. The United States Environmental Protection Agency (EPA) has developed two driving schedules which are widely used for fuel consumption rating. They are:

   - The EPA Urban Driving Schedule (Figure 1), and
   - The EPA Highway Driving Schedule (Figure 2).

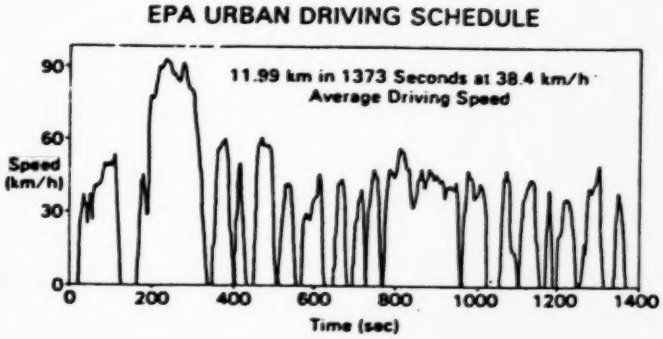


Figure 1

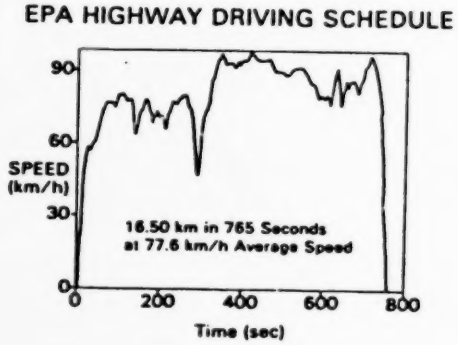


Figure 2

2. These two schedules were used in developing the specification and evaluating the performance of the hybrid vehicle power train concepts. They are significantly different in character. The urban schedule is composed of 18 go-stop cycles with some periods of idling between while the highway schedule represents continuous driving within a single cycle. In each case the vehicle speed is specified at one second intervals. The maximum speed achieved during urban driving is 91.5 Km/hr, while the average speed is 38.4 Km/hr. For the highway driving the maximum speed is 98.4 Km/hr and the average speed is 77.6 Km/hr.

COMPONENT SELECTION

1.0 INTRODUCTION

Market surveys were conducted to establish sources and price availability for the major components required for the advanced hybrid propulsion system. The specialized character of much of the equipment and the relatively low volume requirement resulted in only limited interest by equipment suppliers and, in many cases, only one or two companies responded to request for cost and availability. The selection available was, therefore, somewhat limited.

The components selected are discussed below.

2.0 SELECTION OF COMPONENTS

2.1 Traction Motor

Two manufacturers, General Electric and Leroy Somer, responded to requests for cost and availability data. The Leroy Somer motor is somewhat lighter and smaller than that offered by General Electric and lower in cost, it was selected for the prototype system: its principal characteristics are:

Manufacturer - Leroy Somer,	Agriers, France
Rated Power (kw)	15
Peak Power (2 mins) (kw)	24
Base Speed (rpm)	3200
Maximum Speed (rpm)	8000
Weight (kg)	70
Rated Voltage	120
Rated Armature Current (amps)	150
Rated Field Current (amps)	15

2.2 Motor Controller

The market survey revealed only one production motor controller suitable for adaptation to provide regenerative braking which would be available within the time frame. Outline characteristics are:

2.2.1 Armature Chopper

Manufacturer - PMC,	Berkeley, California
Model	DCC 120
Type - power transistor, pulse width modulation	
Maximum Voltage	140
Maximum Current (amps)	400
Weight (kg)	5

Modification to provide regenerative braking will be carried out by Marathon.

2.2.2 Field Chopper

To be developed by Marathon.

2.3 Motor Transfer Drive

Both toothed (timing) belt and chain drives were considered. The former is not available with sufficient capability to handle the torque developed by the motor at low speeds. The outline characteristics of the chain drive are:

Manufacturer - Morse Power Transmission Products Division, Borg Warner Corporation
Type - Hyvo Chain, with aluminum case
Lubrication - Pressure
Model - Hyvo, HV304, 1.33 ratio

2.4 Engine

A number of suitable gasoline engines are manufactured for "micro cars" in use in Europe and Eastern countries. After examination of power output, economy, availability and servicing requirements the 1 Litre Diahaitsu engine was selected: its outline characteristics are:

Manufacturer - Diahaitsu, Osaka, Japan
Model - CB, 4 cycle, water cooled, 3 cylinder

Displacement	993 cc
Max Power (kw)	41 at 5500 rpm
Max Torque (Nm)	76.5 at 2800 rpm
Min Fuel Consumption (g/kwh)	281 at 2800 rpm
Dry Weight (kg)	86

2.5 Engine Clutch

As supplied by engine manufacturer. Toggle mechanisim and hydraulic actuator to be developed by Marathon.

2.6 Transmission

The transaxle of front wheel drive vehicles is integrated into the chassis design to a higher degree than the transmission of a rear drive vehicle and the freedom to change transmissions is much reduced. The 3 speed automatic transaxle built by Chrysler for the T-115 van is the only practicable selection for a project of the scope of the present development. It is anticipated that a four speed unit will become available in the near future. The use of a developmental transmission such as the Kerr-Train is attractive, however, funding required for development and packaging will be large. Continuously variable V belt and steel belt transmissions offer potentially attractive

performance characteristics and may become available in capacities for vehicles in the weight/power classification of the T-115 van in the next few years. The outline characteristics of the Chrysler automatic transmission are:

Manufacturer	Chrysler Corporation
Type	3 speed automatic with torque converter
Throttle Valve Control	Mechanical
Gear Ratio	2.84, 1.6, 1.0:1
Final Drive	3.13:1

To be Developed by Marathon:
- new gear sets to provide final drive ratio
- external drive for front pump
- new clutch/convertor housing
- minor oil circuitry modifications
- throttle valve modulation

2.7 Transmission and Steering Pump-Service Motor

This motor has not been selected pending completion of tests to confirm power requirements. 0.5 - 5 HP DC motors are available from General Electric and Morse Transmission Products.

2.8 Power Brakes

The Bendix Hydro Boost II has been selected to replace the standard vacuum boost system.

2.9 DC DC Convertor for Vehicle Service Electrical System

Manufacturer	Marathon
Model	Special Development
Input Voltage Range	120 - 98
Output Voltage	14
Output Amps	35
Efficiency at 20A	75%

2.10 Traction Batteries

The selection of the traction batteries is based on manufacturers claims for energy and power density, peak power, life cycles, cost and installation factors (e.g. operating temperatures). While developmental batteries such as Aluminum - air, Lithium metal sulphide, Zinc - Bromine, etc. offer advantages in the long term and Nickel-Iron batteries which have been in development for 80 years have some promise, only lead acid batteries are proven and available at reasonable cost at present. Batteries have a life of three to four years in service and as more advanced battery systems are developed they can be taken into service as replacements for the lead acid system.

Among the lead acid systems the Furakawa battery offers the best combination of characteristics. The outline characteristics of the selected battery are:

Manufacturer - Furakawa Battery Co. Ltd., Tokyo, Japan	
Model	EL 130
Voltage	12
Capacity 1 hour rate (AH)	99
Capacity 5 hour rate (AH)	140
Weight (kg)	39
Energy Density (Wh/kg)	43
Power Density (W/kg) at 25% DOD	71
Cycle Life (60% DOD)	1000
Construction	Tubular Cathode

Ten 12 volt batteries conforming to the above specification will be employed providing 16.8 Kwh at the 5 hour rate.

2.11 Vehicle Control System

The system will be built and developed by Marathon. The microcomputer based hardware will be divided into two or three parts on separate boards. Each board will have a separate microcomputer. Basic hardware will be evaluated and selected as the design is developed. Software systems for each microcomputer will be developed to meet the r equirements of the controller functions.

APPENDIX G

HYBRID VEHICLE SIMULATION PROGRAM

This program was developed based on HYVEC vehicle simulation program developed by General Electric. The reason behind this development is during the preliminary design stage of the vehicle it was a definite necessity to perform a simulation quite frequently on easily accessible computer which was IBM-PC-XT. The original HYVEC consists of approximately 6000 lines of Fortran source code and is divided into 50 subroutines, which is beyond the capacity of IBM microcomputer. Also numerous features are included in the program which are not quite necessary for the performance and economy estimation. Therefore for Marathon's VHSP, all unnecessary features and subprograms are omitted and also it was made to minimize the complexity of operation and input data generation. However it has sufficient capability to estimate acceleration, energy consumption, maximum speed, gradeability, range, etc. with essentially identical accuracy with HYVEC.

The vehicle behaviour can be simulated basically in two ways:

a) Gas pedal position input (brake pedal force as well)

b) Speed input

The pedal position input can be used for maximum performance estimation as well as monitoring vehicle response to an input from driver.

Speed input was intended to estimate fuel economy for various driving patterns. Currently the EPA urban mode is built in the form of speed vs time table. By this table, actually also acceleration is specified since the speed at a moment and that of one second later is also specified. When the vehicle is not capable of achieving this acceleration, it issues warning and maximum possible accele3ration is assumed instead. When an extraordinary speed-time pattern is specified, it would be noticed since gas pedal position given as an output data will behave abnormally.

HVSP consists of 15 to 17 subprograms many of whic actually simulate single component. For example subroutine "Engine" calculates torque of power and fuel consumption at a given engine4 speed, throttle opening temperature, pressure and rate of angular acceleration.

Other components simulated and built in a subprograms are:

1) Electric Motor
2) Battery
3) Motor Controller
4) Transmission (automatic)
5) Propulsion System Controller

As can be noticed, subroutine (5) Propulsion System Controller is virtually identical to acutal VPSC program described in Appendix H. The actual VPSC program to be loaded into VPSC computer ROM is, without doubt, best suited for simulation. Also by running HVSP, debugging and function monitoring can be achieved at the same time.

The HVSP program, to be run correctly, needs too be supplied with accurate representation of motor or engine performance as well as battery or motor controller performance curve. The basic operation of the program is, in the case of speed input run as in the EPA urban mode simulation,

1) taking the speed and acceleration required from the specified speed diagram

2) determine the engine (or motor) speed and torque

3) consulting the engine (or electric motor) performance curve, determine the efficiency and fuel (energy) consumption for the specific load and speed for the period of one second

4) taking renewed speed for one second later, repeat the procedure (1) to (3), and at each cycle add up all parameters such as energy consumption, distance travelled, etc.

The above description is, of course, radically simplified and it should be noted that in each operation efficiency or loss of all components are taken into account by consulting the table and predetermined formulae in some cases. For example, transmission efficiency is expressed by speed and torque for each gear position in several formulae but battery discharge characteristic is completely tabulated versus current and DOD, etc.

The energy consumption figures used in economic analysis were produced by original HYBEC, not by Marathon HVSP, with proper representation and input data for this specifically configured T115 Hybrid van. As listed in Appendix I, characteristics of Daihatsu 3 cylinder 998 cc CB-30 engine and Leroy Sommer 10 inch diameter separately wound motor.

APPENDIX H

VPSC Program Specification and Description

This document explains and specifies how power sharing scheme is implemented in the VPSC computer program.

Basic operation is as follows:

1) According to the gas pedal position (θ acc) and drive axle speed (WI), the requested torque (% Treq) relative to maximum available is determined with reference to the formula I which represents θ acc - % Treq relation shown on Figure 1.

2) The total torque requested (Treq) is calculated by multiplying the maximum torque available shown in Figure 2 by % Treq obtained in procedure (1).

3) When in electric motor mode (E.M.mode), i.e. vehicle speed is below Vmod, electric motor supplies the requested torque and when Treq exceeds the motor's capacity, the heat engine supplements.

4) When in heat engine mode (H.E.mode), the heat engine works as the primary power source and supplies torque (THE) which is between 20% and 100% of its maximum.

Above explanation is overly simplified, however the vital function of this routine, namely power sharing, is handled in relatively simple manner.

Hysterisis and some other techniques are built in to avoid hunting and to attain maximum fuel efficiency.

Figure 1 gives Maximum Torque Available (Ttot) max
Maximum Torque by Heat Engine (THE) max
Maximum Torque by Electric Motor (TEM) max

Given % Treq (shown in Figure 2), and Actual requested torque (Treq) is calculated:

Treq = % Treq x Ttot

POWER SHARING SCHEME

A) In Electric Motor Mode

Op. mode 1. When Treq < (TEM)max Treq.EM = Treq

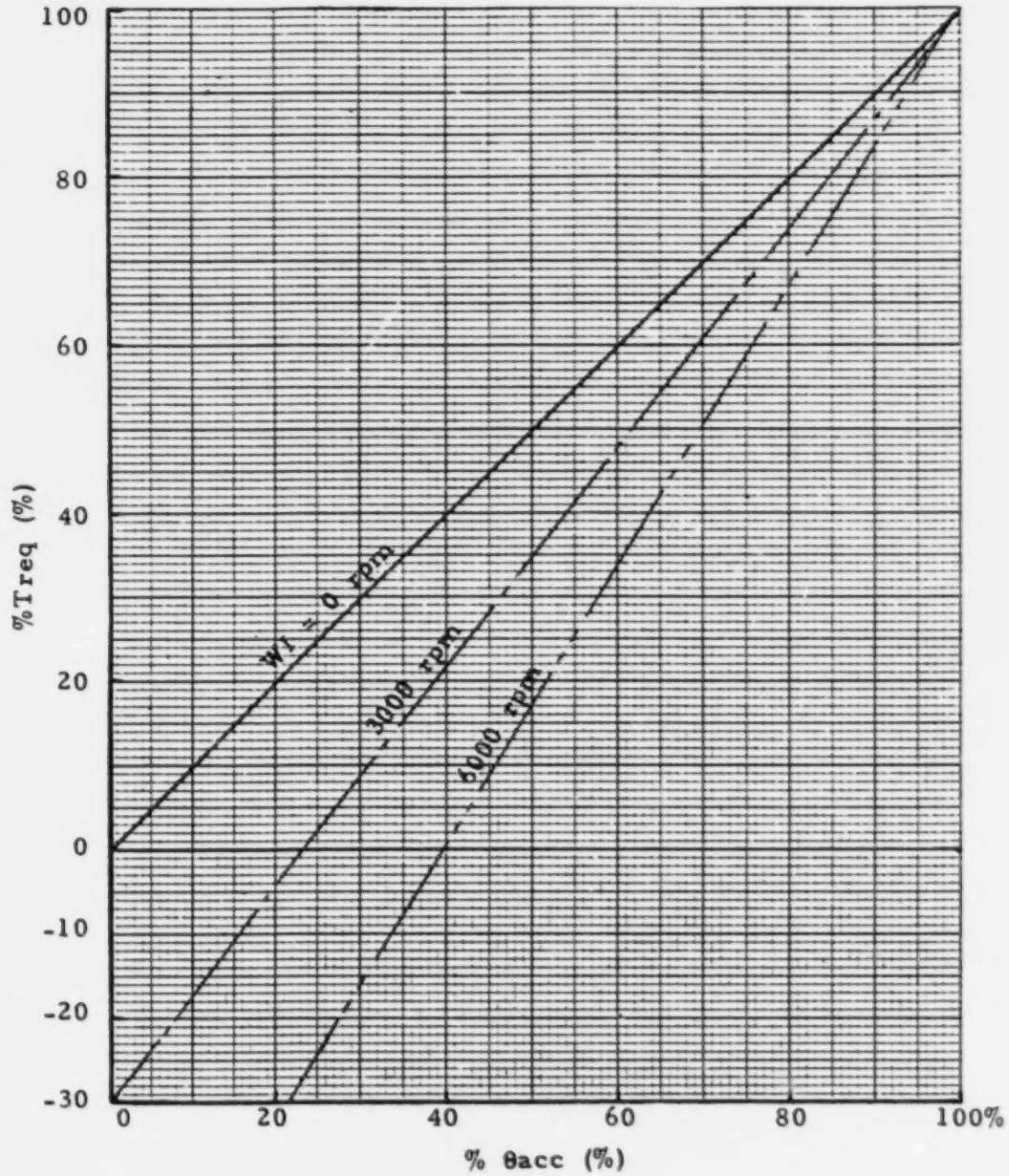
Op. mode 2. When Treq is increased to Treq > (TEM)max
Treq.EM = Treq-(THE)opt

Where (THE)opt is the optimum torque for heat engine shown in Figure 3.

Figure 1 - Requested Torque v.s. Gas Pedal Position

θacc: (Accelerator pedal position)

%Treq: (Torque requested relative to maximum torque available at given motor speed)



Formula for above relation

%Treq = (% θacc - 100) x a + 100 : a = 1 + WI/10000

: WI : Transmission drive axle speed

When %Treq ≤ -30 then %Treq = -30

Figure 2 - Maximum Available Torque

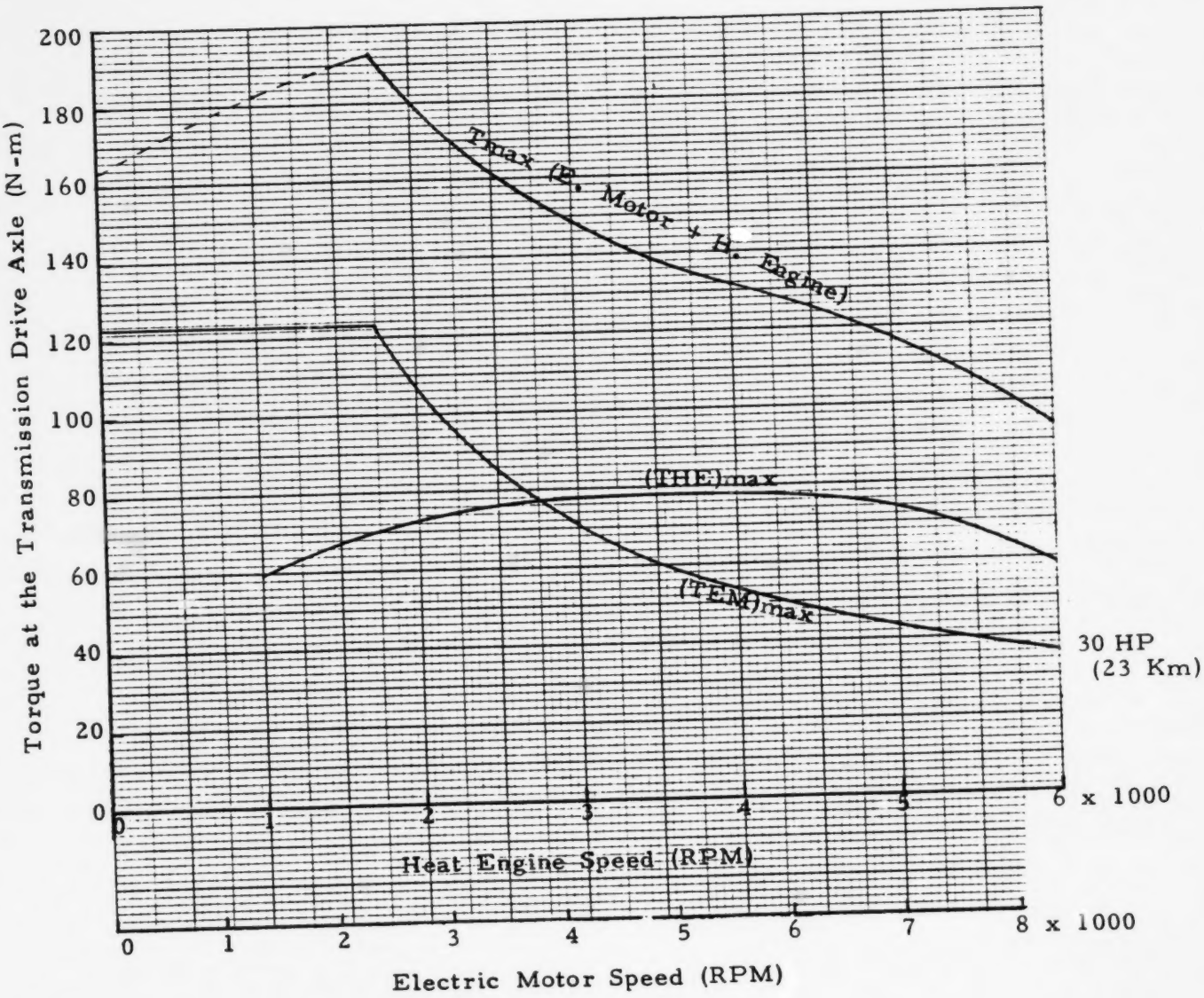
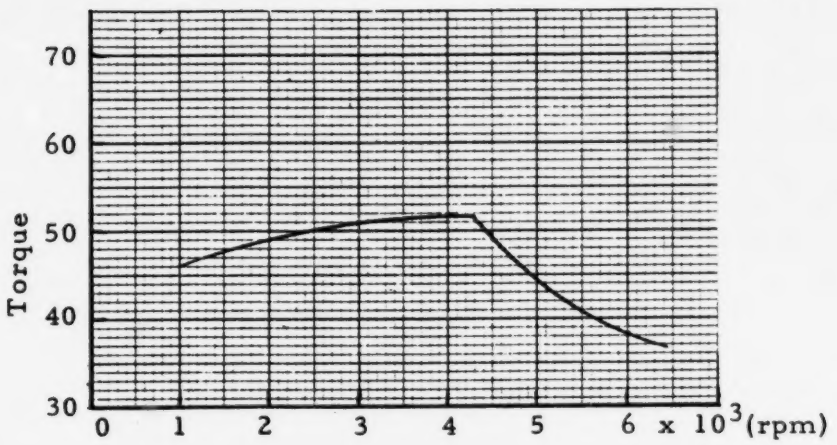


Figure 3

(THE)opt Optimum Engine Torque

up to 4300 rpm
PMAN = -180mmHg constant
over 4300 rpm, same as (TEM)max



WI (Transacle Drive Shaft Speed)

And set Treq.HE = (THE)opt and immediately Heat Engine is started

Op. mode 3. When Treq > (THE)opt + (TEM)max
Treq.EM = (TEM)max and Treq.HE = Treq-(TEM)max

Op.mode (2)', Even when Treq is decreased to Treq < (TEM)max, Heat Engine is not shut down immediately; only when Treq is decreased to Treq < (THE)min, the Heat Engine is shut down and operation mode becomes (1). (Where (THE)min is minimum heat engine torque) Therefore operation mode becomes (2)' only when Treq is decreased to (THE)min < Treq < (TEM)max.

It is needed to prevent too frequent transition from E.Motor only mode to both H.Engine and E.Motor combined mode.

a) Therefore when θacc is increased and Treq becomes larger than (TEM)max, H.E. is started. But H.E. is not turned off until Treq falls to (THE)min (this is, so to speak, introduction of hysterisis).

b) When θacc is increased and Treq becomes 95% of (TEM)max, accelerator pedal pusher is actuated (accelerator pedal becomes heavier to depress) and tells driver that Treq.EM is close to limit (through an indicator). Once the heat engine is started the accelerator pedal pusher is deenergized only after Treq falls below (THE)min. Therefore this happens simultaneously with H.Engine shut down, and encourages driver to shut down the engine.

POWER SHARING SCHEME

B) Heat Engine Mode

1. When Treq < (THE)max TreqHE = Treq

2. When Treq > (THE)max TreqHE = (THE)max and TreqEM = Treq - (THE)max

3. When Treq falls to Treq $\leq$ (THE)min x 0.5(*)
   TreqHE = 0 but H.E. idles as long as Vv > Vmod.
   TreqEM = 0

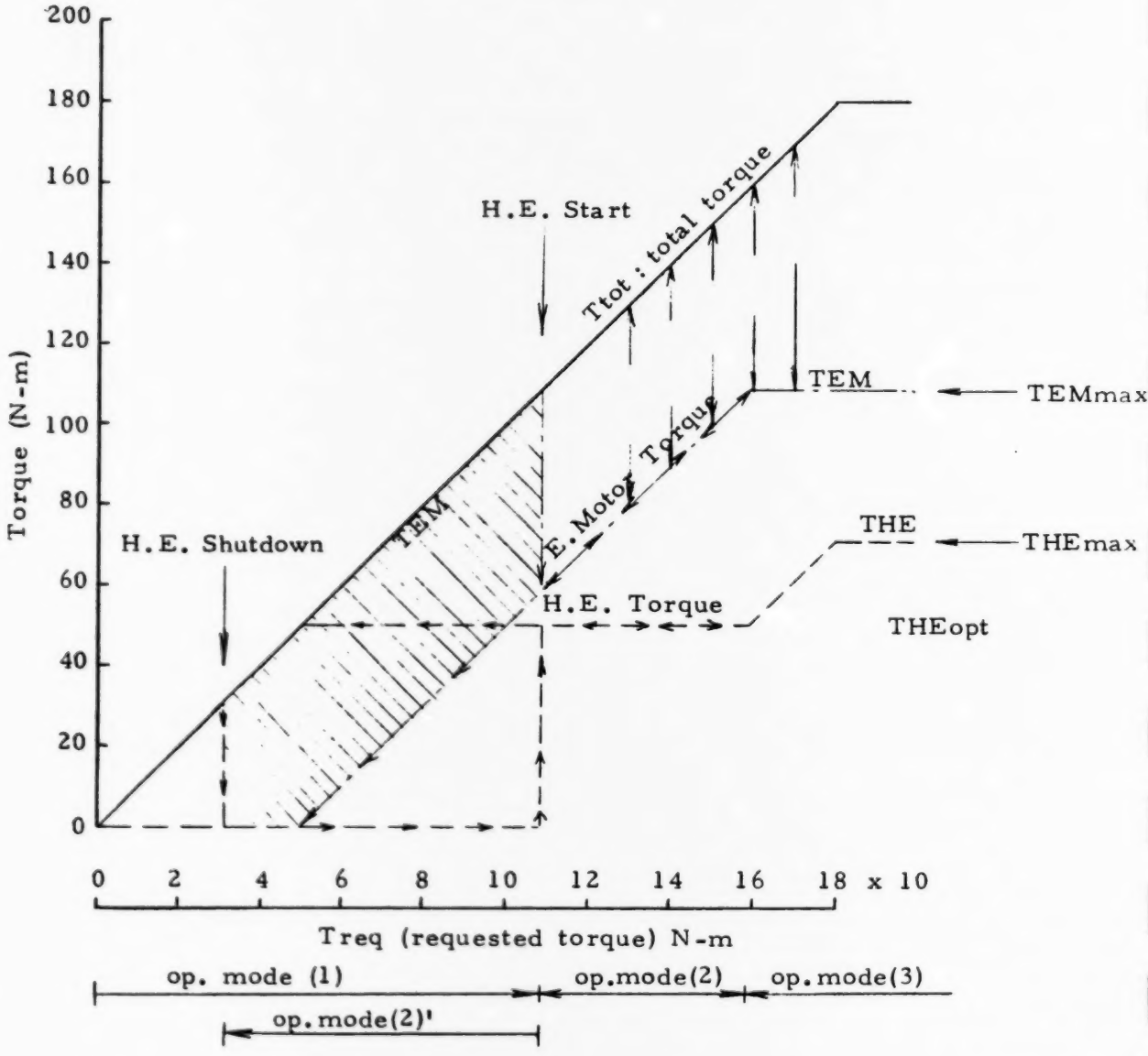
   (*) with this torque level, PMAN = -440mmHg and SFC is 350 - 400 gr/Ps.hr

As in above, the power sharing is simple. Only when the torque request exceeds maximum available torque of heat engine, electric motor helps engine, and it does not come on in any other case. When the torque request is too small, the request is ignored to avoid uneconomical operation. This level is only 9 - 18% of total available torque, therefore it is not too significant to the driver.

Figure 4

Example of Power (torque) Sharing Scheme

at 2000 rpm WI



** Hysteresis (31 N ~ Treq ~ 109 N)

The heat engine provides power for the shaded area in the graph when the engine is already running, namely only when Treq is <u>decreased</u> into this range heat engine continues to supply power. When the heat engine is not started yet, the electric motor supplies the power.

Coasting

This occurs only during heat engine mode.

When TreqHE falls below 50% of (THE)min (approximately 440 mm Hg of manifold vacuum), clutch is disengaged and engine idles. This procedure is almost instantaneous.

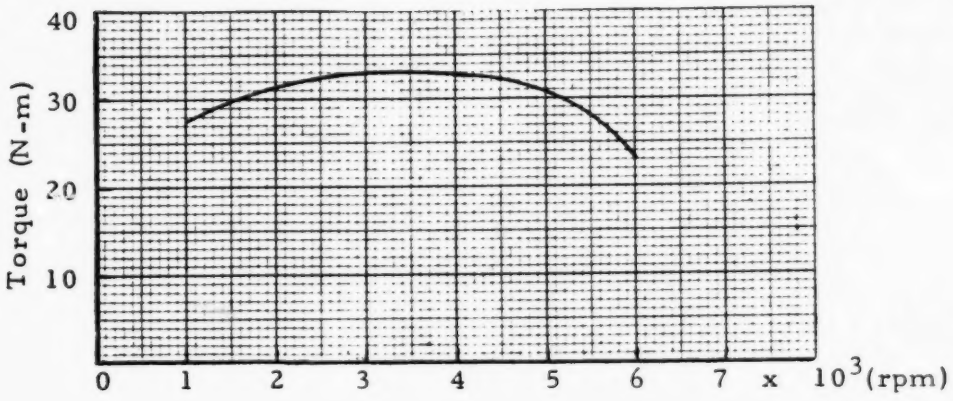
When TreqHE increases up to 80% of (THE)min, clutch engagement and appropriate carburetor throttle opening occurs simultaneously. (See Clutch Re-engaging Procedure)

During coasting, heat engine keeps idling as long as the vehicle speed (Vv) is above Vmod.

When % Treq falls below -10%, moderate regenerative braking is applied in order to simulate so called "engine brake". (See Regenerative Braking)

Figure 5

(THE)min for Daihatsu CB30 Engine



WI

And in Op. mode (2)'

when Treq $\geq$ (THE)opt TreqHE = (THE)opt, TreqEM = Treq-(THE)opt

when Treq $\leq$ (THE)opt TreqHE = Treq, TreqEM = 0

Figures 4-A, 4-B describe the total torque sharing scheme at 2000 rpm - 4000 rpm WI respectively.

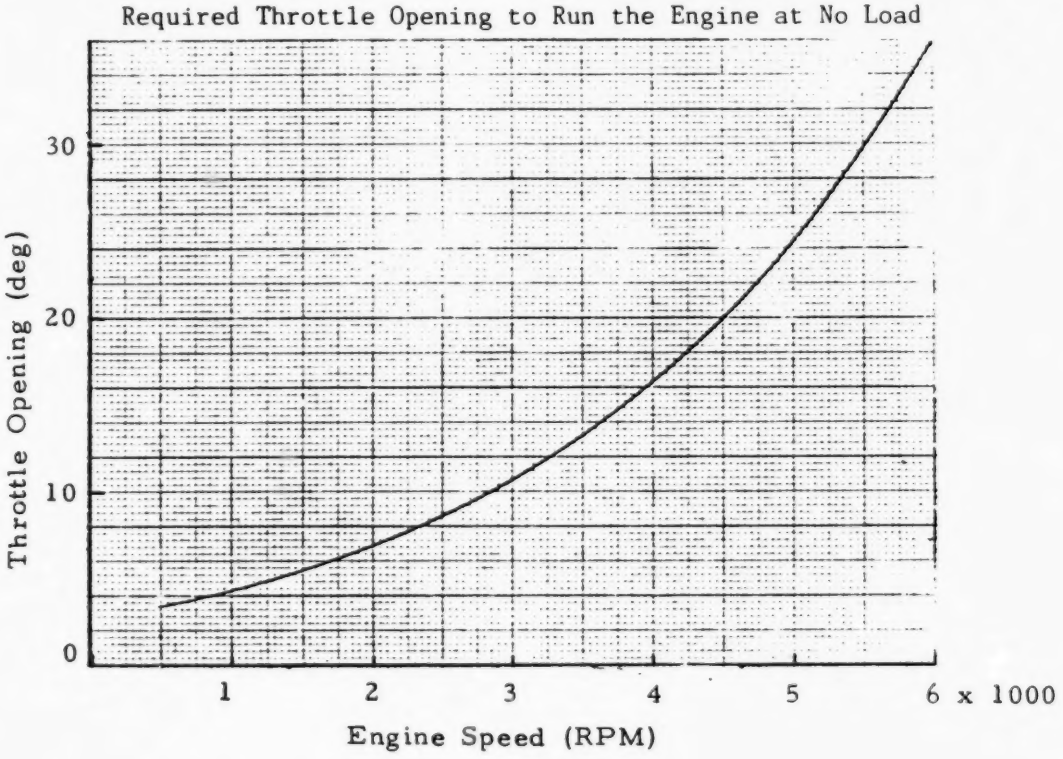
Clutch Reengaging Procedure

1. Read E.M. speed and calculate Nhe.cal = NEM/RRTO1 (RRTO1:reduction ratio between EM & HE = 1.40).

2. Open the clutch engage valve and verify if disengage valve is closed (if not, close it).

3. Read required throttle opening from Figure 7.

Figure 7



4. Set throttle to the specified value in Step 3.

5. Clutch Engage Routine (CER) Flag ON and jump to Main Routine. Come back after 1 cycle of Main Routine execution (30 msec).

6. When CER Flag is ON any command set for carburetor throttle opening is overridden by the value specified by CER and comes back to Step 7 of CER routine.

7. If clutch position becomes engaged? If even after 200 cycle (6 sec) clutch does not engage, clutch failure flag (CF Flag) ON and turn off clutch valve, go to Main Routine.

   Yes - Turn OFF CER Flag and go to Main Routine. End.
   No - Without turning off CER Flag, go to Main Routine.
   Kounter = Kounter + 1.

Regenerative Braking

There are three stages of regenerative braking.

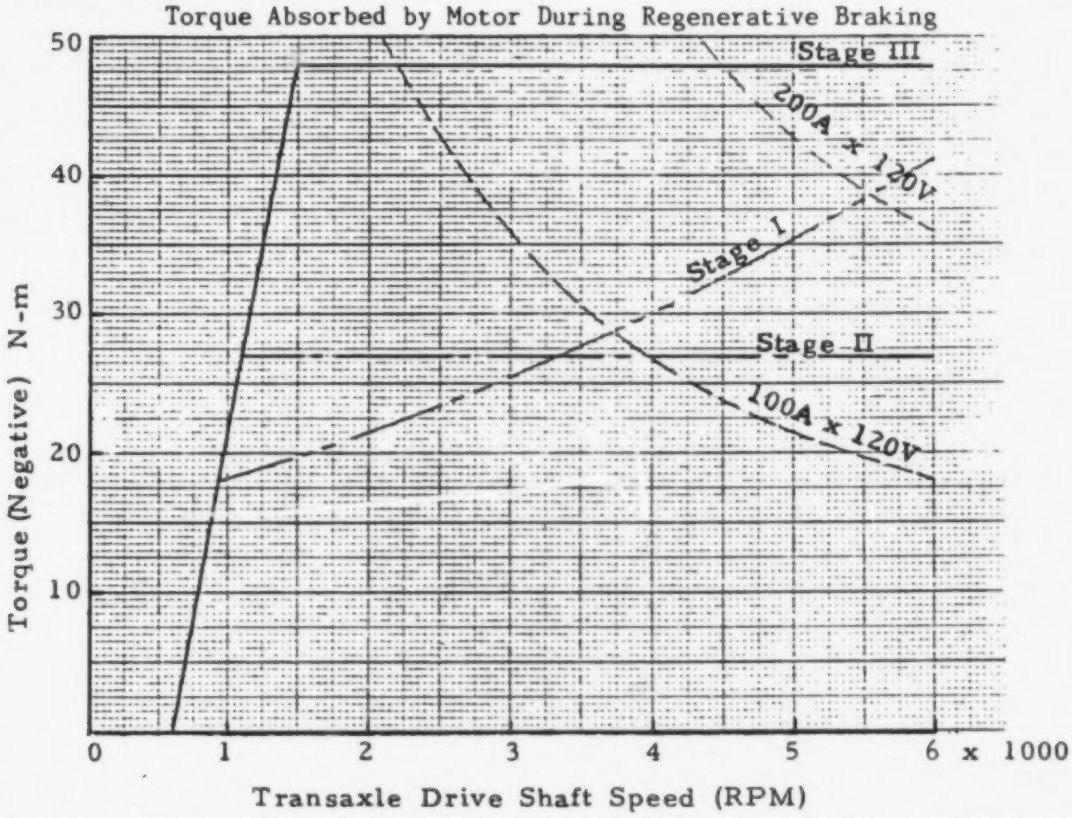
Stage I Accelerator pedal is released.

Stage II Brake Pedal is slightly depressed.

Stage III Brake Pedal is depressed further but not to the extent where the friction brake is applied.

When both brake and accelerator pedal are depressed, E.M. absorbes the torque indicated in Figure 8. But H.E. provides torque as if brake pedal is not depressed. Therefore in H.E. mode the driver can recharge battery at will.

Figure 8

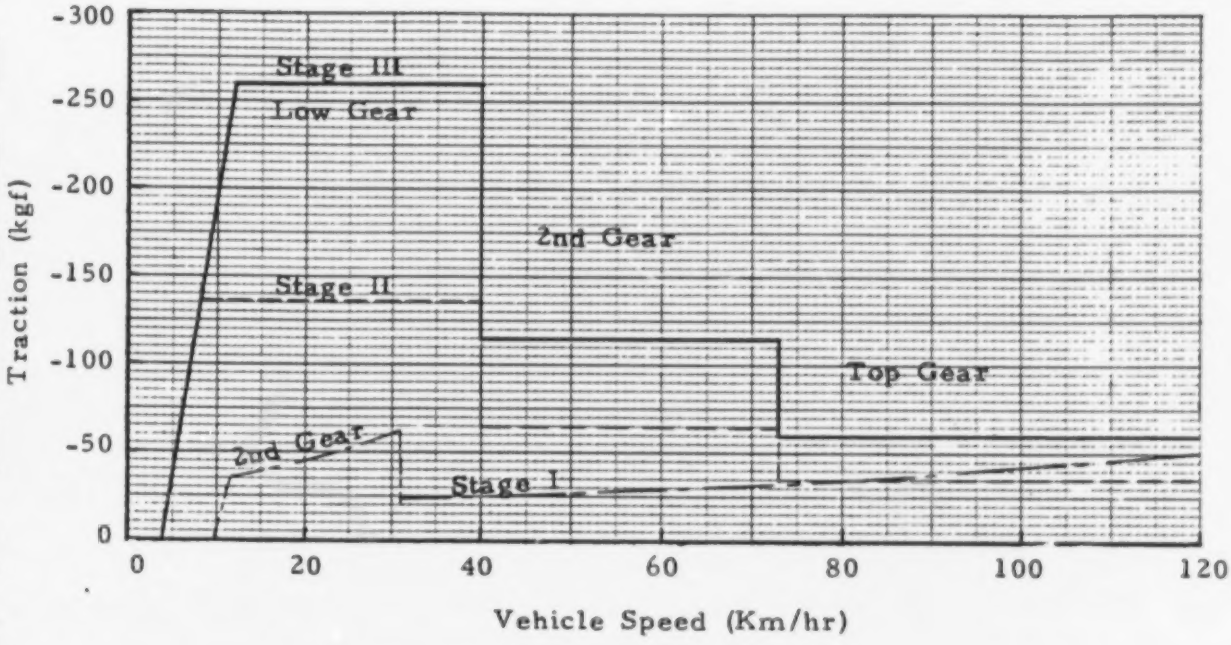


When brake pedal is depressed, regeneration and field reverse contactor (see Figure S-5) is actuated and field polarity is reversed to enable efficient regeneration at low motor speed. And at the same time, transmission manual valve overrider (TMMVO) is actuated to select the lowest possible gear. Therefore traction (negative) during regenerative braking becomes higher at low speed because of automatic shiftdown.

However the gear shiftdown at high speed does not occur for Stage 1, since an ordinary car with automatic transmission does not have a strong engine brake effect or shiftdown characteristics in "Drive" position.

Figure 9

Negative Traction During Regeneration
(accelerator pedal not depressed)



Control Procedure for Regenerative Braking

1. When % Treq remains below -10% for 5 consecutive computer cycles, or brake pedal is depressed, regenerative braking flag (RBF) is turned on (in the Main Routine) and Regenerative Braking Routine (RGB1,2) is called. Stage number (1,2,3) is stored in Main Routine.

2. In RGB 1,2 if field reversed? Yes jump to b)

   a) No - Subroutine named SPCHG is called to activate relay 1 & 2 which reverses field polarity.

   b) Calculate requested negative torque (TNreq) according to the table (shown in Figure 7).

   c) Calculate required field voltage (FIcom) and optimum duty cycle for motor armature from WI (input shaft speed) and TNreq. This table is different from the one used in the Main Routine.

   d) RETURN

Battery Recharge (Stage 1)

When BSOC falls below 28%, the controller selects charging mode Stage 1. In this mode, battery recharge is performed only when the power demand for H.E. is too low to maintain economical engine operation. This is likely to occur during low speed cruise or slight deceleration. Needless to say, battery recharge is performed only in H.E. mode.

1. When Treq falls to TreqHE = Treq < (THE)opt x 0.8 (but Treq $\geq$ 0)

   TreqHE = (THE)opt

   oReset

   TreqEM = Treq - (THE)opt < 0 Negative

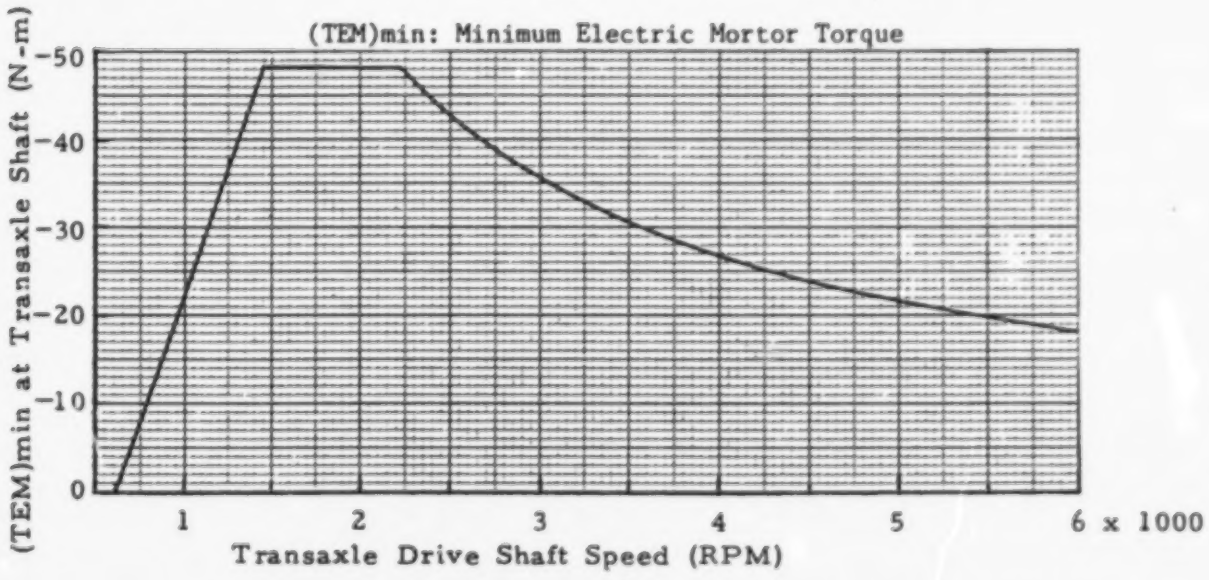
   but when TreqEM < (TEM)min ((TEM)min is negative)

   TreqEM = (TEM)min and TreqHE = Treq - (TEM)min

   Therefore Ttot = TreqHE + TreqEM = Treq

   (TEM)min represents -100A current line.

Figure 10



3

Note: WI never reaches 4 - 4.5 x 10 rpm because θacc is relatively low and transmission shifts up. Therefore TreqHE never falls below 2.5 kg-m maintaining good SFC.

When Treq increases to Treq > THE, TreqHE = Treq
TreqEM = 0

2. When Treq becomes Treq > (THE)max PSCHG is called, and system resumes ordinary hybrid operation.

3. When % Treq becomes % Treq < -10% ordinary regenerative braking is applied.

Battery Recharge (Stage II)

When BSOC becomes 25% or lower, the controller selects charging mode Stage II. Since BSOC is low, Vmod is the lowest and the vehicle runs in H.E. mode in all cases but at rest.

Even in this mode, battery is charged only when engine is capable of providing surplus power, such as during cruise, moderate acceleration and deceleration.

To obtain more surplus power from H.E., transmission throttle valve overrider (TMTVO) is actuated so that engine keeps running at high speed.

1. When battery recharge stage II flag on

   a) TMTVO is actuated (whenever BR Stage II flag is on)

   b) When Treq falls to $0 < Treq < (THE)max \times 0.8$, SPCHG is called

      set TreqHE = (THE)max

      TreqEM = Treq - (THE)max (< 0)

      but when TreqEM < (TEM)min < 0

      TreqEM = (TEM)min 100A limit

      TreqHE = Treq - (TEM)min

2. When Treq increases to Treq $\geq$ (THE)max, PSCHG is called and the system resumes ordinary hybrid operation.

3. When % Treq becomes % Treq < -10%, ordinary regenerative braking is applied. However RGB Stage I is as strong as Stage II since already TMTVO is actuated.

Battery Recharge (Stage III)

When BSOC falls below 20% system selects battery recharge Stage III mode and battery is charged almost all the time.

Because this mode is an emergency mode, BSOC warning lamp in dash panel is lit telling the driver that E.M. is not available.

When BSOC falls below 20%, battery recharge (BR) Stage IV flag is turned on.

When in BR Stage III mode, motor field contactor is always in reversed position and TMTVO is actuated.

Always set TreqHE = (THE)max

and TreqEM = Treq - (THE)max

but when TreqEM > 0 --> TreqEM = 0

Also when TreqEM < (TEM)min * 1.5

TreqEM = (TEM)min * 1.5

set

TreqHE = Treq - (TEM)min * 1.5

Note (TEM)min < 0

4. As in (2), no E.M. power is supplied.

5. As in BR Stage II, regenerative braking (RGB) Stage I is as strong as RGB Stage II.

Cold Weather Operation

When ambient temperature is below 10 °C, cold weather (CW) flag is turned on.

While CW flag is on, system tries to keep the engine coolant temperature higher than 40oC at all time.

When heater switch is turned on, the control system tries to keep the engine coolant temperature higher than 60oC all the time.

When ambient temperature is below 15 °C, CW flag is turned on.

While CW flag is on:

1. When coolant temperatue falls below 30 °C H.E. is started and idles at 1500 rpm.

2. Vmod = Vmod * 0.5 Vmod is reduced to a half of the original value.

3. Even during electric motor mode (Vv < Vmod), H.E. keeps idling at normal speed (900 rpm) as long as coolant temperature is below 60oC.

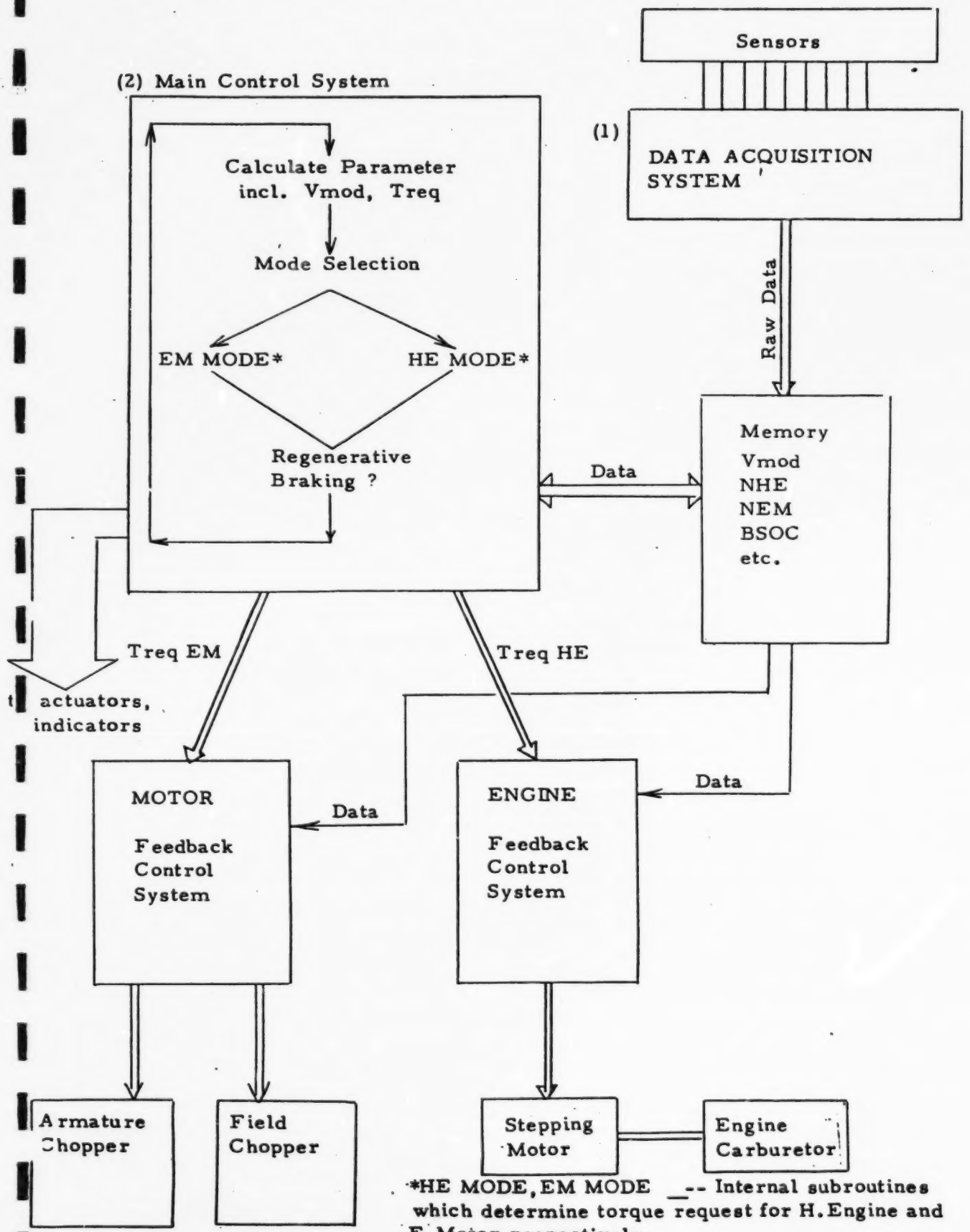
LIST OF VARIABLES

FVmes req	Field Voltage	(V)
FImes req	Field Current	(A)
AVmes req	Armature Voltage	(V)
AImes	Armature Current	(A)
OTH(θth)mes req	Carburetor Throttle Opening	(%)
OACC(θacc)	Accelerator Pedal Position	(%)
PMAN	Manifold Vacuum Pressure	(mmHg)
NEMmes	Electric Motor Speed (rpm)	
NHEmes cal	Heat Engine Speed (rpm)	
WI	Transaxle Input Shaft Speed (rpm) calculated from NEMmes	
Vv	Vehicle Speed	
Vmod	Vehicle critical speed for mode change	
Subscript	mes : measured and corrected to specified unit req : requested, given from controller cal : calculated no subscript means measured value, except for Vmod	
Treq	Requested Torque (Total)	
TreqEM	Requested Torque for Electric Motor	
TreqHE	Requested Torque for Heat Engine	
(TEM)max		
(THE)max		
(THE)opt		
(THE)min		
SFC	Specific Fuel Consumption	

LIST OF SENSORS

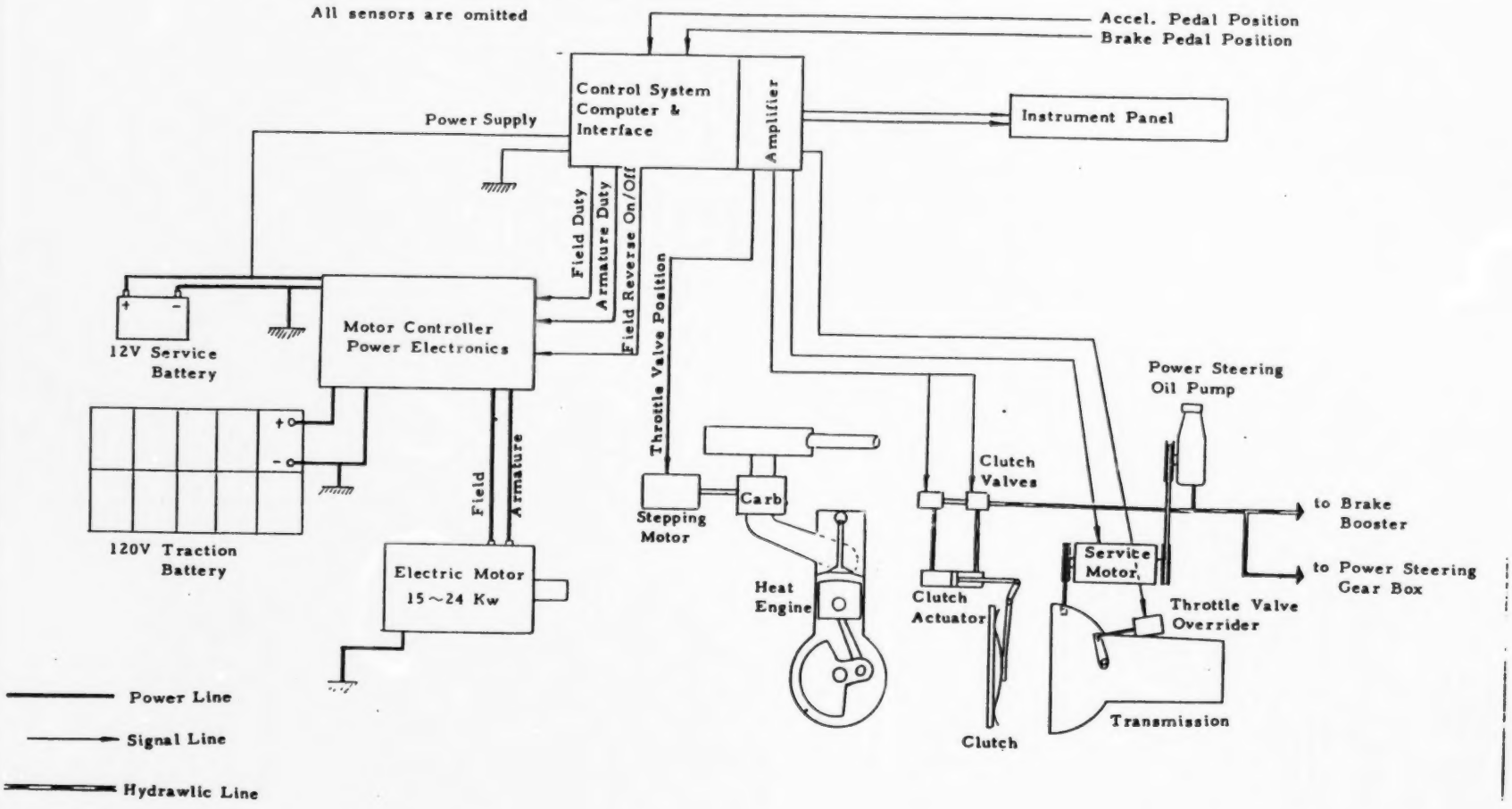
	Sensor	Comment
Speed		
Vehicle Speed	Pulse Counter Magnet Inductor	at Transaxle Gear
Electric Motor Speed	Pulse Counter	at E. Motor Shaft
Heat Engine Speed	Pulse Counter Magnet Inductor	at H.Engine Flywheel
Driver Input		
Accelerator Pedal Position	Potentio Meter	
Brake Pedal Position	Potentio Meter	
Heat Engine Power		
H. Engine Manifold Vacuum	Strain Gauge Type or Semiconductor Pressure Transducer	widely used for EFI
Current		
E. Motor Current (Armature)	Hole Effect Magnetic Field Sensor	
E. Motor Field Current	Shunt Resistor	
Voltage		
E. Motor Armature Voltage E. Motor Field Voltage Battery Voltage	All voltage can be directly measured therefore no sensor is required.	
Temperature		
Ambient Temp. Battery Temp. Heat Engine Coolant Temp. Electric Motor Temp. Motor Controller Temp.	Semiconductor Temperature Sensor or Thermister.	

Control System Block Diagram



*HE MODE, EM MODE -- Internal subroutines which determine torque request for H. Engine and E. Motor respectively.

System Diagram - Major Components and Connection



VPSC Program

Source Code List

```
C                ***********************
C                *HYBRID VPSC PROGRAM*
C                ***********************
C        MAIN ROUTINE IS TEMPORARILY SET UP TO TEST VPSC PROGRAM
C        ACTUAL VPSC PROGRAM STARTS FROM SUBROUTINE "CYCLE"
C        HYBRID VEHICLE VPSC PROGRAM
      DIMENSION ACCG(300),VVV(300),ACCL(300),TOREQ(300),
     *TRQEM(300),ATRAC(300),TIME(300),AWI(300),TRQHE(300)
     *,OACCC(300)
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      COMMON /SLOW/BSOC,BSOC1,BSOC2,TAMB,TBATT,TENG,TEM1,TEM2
      COMMON /ELMTR/TREQEM,TEMMAX,TEMMIN,CARM,CARMRQ,
     *CFLD,CFLDRQ,EARM,EFLD,EFLDRQ
      COMMON/HENGN/TREQHE,THEMAX,THEOPT,
     * THEMIN,SFC,PMAN,OTH
      COMMON /STATUS/ ICOND, KNT, ICHG
C        MAIN PROGRAM
C        INITIALIZATION
C           INITIAL VELOCITY
         VI=0.
C
         ACC=.5
C           WV:VEHICLE WEIGHT
         WV=1973.
         RTO=1.4
         TB=.5
         NNN=300
         VVH=VI
         BSOC=.8
         OACC=100.
         GR3=1.
         GR2=1.6
         GR1=2.84
         FA=27.4*.3047**2
         CD=.43
         DO 5 I=1,30.
    5    IFLAG(I)=0
C        WRITE(4,401)
C        WRITE(4,440)
C440   FORMAT(1HO," SPEED TORQUE FLAGS(1-14)   TRAC.   DRAG    WI
C    *TREQHE TREQEM TREQ OACC")
         DO 10 I=2,NNN
         WI=VVH/.023
         WI2=WI*(GR2/GR3)
         WI1=WI*GR1/GR3
         INDAC=1
         IF(ACC.LT.0.)INDAC=-1
         RTRNS=TRANS(OACC,INDAC)
         IF (WI2.LT.RTRNS) WI=WI2
         IF (WI1.LT.RTRNS ) WI=WI1
C         WRITE(1,101)
  101    FORMAT(1H ,"JUST BEFORE CALLING TABLE")
         CALL CYCLE
C         WRITE(1,133)
```

```
  133    FORMAT(" CYCLE ENDED")
         TORQUE=TREQHE+TREQEM
         TRAC=16.3909*TORQUE
         IF (WI.EQ.WI2) TRAC=TRAC*GR2
         IF(WI.EQ.WI1)TRAC=TRAC*GR1
         CALL DRAG(VVH,WV,FA,CD,DRG,HP)
C        WRITE(1,135)
  135   FORMAT(" DRAG ENDED")
C        ACCELERATION
         I3=I-1
         ACCL(I3)=      (TRAC-DRG)/WV
         ACC=ACCL(I3)*9.806
         I2=I+1
         VVH1=VVH+ACC*TB*3.6
C         ACCG(I)=WV/TRAC
C        DIST(I) =TB*(VVH1+VVH)/7.2+DIST(I-1)
C        WRITE(4,407)VVH,TORQUE,(IFLAG(J),J=1,14),
C    *   TRAC,DRG,WI,TREQHE,TREQEM,
C    * TREQ, OACC
C407     FORMAT(1H , 2(F6.2 ),1X,14I1,3(1X,F7.2),3(1X,F5.2),1X,
C    * F6.2)
       I3=I-1
       VVV(I3)=VVH
         VVH=VVH1
C     TEMPORARY ACCEL PEDAL MANIPULATION
         IF(VVH.GT.50.)OACC=0.
         IF(OACC.LE.0.AND.VVH.LT.30.)IFLAG(30)=1
         IF(IFLAG(30).GE.1)OACC=COS(FLOAT(I)/10.)*40.+43.
    *    +SIN(FLOAT(I)/3.7 )*6.
C       IF(NN-25.LE.I.AND.VVH.LT.80.)OACC=FLOAT(N-I)*5.
         IF(OACC.LT.0.)OACC=0.
         IF(OACC.GT.100.)OACC=100.
C ******************************************************


       TIME(I3)=FLOAT(I3)*TB
       OACCC(I3)=OACC
       ATRAC(I3)=TRAC
        TRQHE(I3)=TREQHE
        TRQEM(I3)=TREQEM
       AWI(I3)=WI
       TOREQ(I3)=TREQ

C      WRITE(1,195)I
  195  FORMAT(" ",I4,"TH LOOP ENDED")
  10     CONTINUE
C         WRITE(4,401)
C 401    FORMAT(1HO,20X,"HYBRID VEHICLE SIMULATION  ",
C    *  /     21X,      "************************"/)
C    *   2(5X," TIME",5X,"SPEED",5X,"ACCEL.",4X,"FLAGS(1---14))
C      DO 20 I=1,NNN,2
C       TIME=(FLOAT(I)-1.)*TB
C      TIME2=TIME+TB
C      I2=I+1
C       WRITE(4,405)TIME,VVH,ACCG(I),DIST(I),TIME2,VVH,ACCG(I2)
```

```
C     * ,DIST(I2)
C 405  FORMAT(1H ,8(1X,F9.3))
C 20   CONTINUE
C      WRITE(4,666)I
C666   FORMAT(" ",I7)

       CALL RGRAPH(TIME,VVV,299,200.,10.,0.,15,
     * 100.,20.  ,0., 5,0,"    VEHICLE SPEED (KM/HR)       ",
     * "  TIME (SEC)   ","                ",200,200)

       CALL RGRAPH(TIME,AWI,299,200.,10.,0.,15,
     * 100.,1000.,0., 5,20,"     ENGINE SPEED  (RPM)       ",
     * "  TIME (SEC)   ","                ",200,800)

       CALL RGRAPH(TIME,ATRAC,299,200.,10.,0.,15,
     * 100.,100.,0., 5,40,"      TRACTION  (KG)            ",
     * "  TIME (SEC)   ","                ",200,1400)

       CALL RGRAPH(TIME,TRQEM,299,200.,10.,0.,15,
     * 100., 5.,-5. , 4,60,"     E.MOTOR TORQUE(KGM)       ",
     * "  TIME (SEC)   ","                ",200,2000)
C  CHANGE PAPER

       WRITE(1,554)
  554  FORMAT("  Change Paper,and press  R  when ready")

  556  READ(1,555)RRR

  555  FORMAT(  A1)
       IF(RRR.NE."R")GO TO 556

       CALL RGRAPH(TIME,OACCC,299,200.,10.,0.,15,
     * 100.,20.  ,0., 5,0," GAS PEDAL POSITION (%)        ",
     * "  TIME (SEC)   ","                ",200,200)

       CALL RGRAPH(TIME,TOREQ,299,200.,10.,0.,15,
     * 100.,   5.,-5., 5,20," TOTAL REQUESTED TORQUE(KGM)   ",
     * "  TIME (SEC)   ","                ",200,800)

       CALL RGRAPH(TIME,TRQHE,299,200.,10.,0.,15,
     * 100.,  2.,0., 5,40,"  HEAT ENGINE TORQUE(KGM)      ",
     * "  TIME (SEC)   ","                ",200,1400)

       CALL RGRAPH(TIME,ACCL ,299,200.,10.,0.,15,
     * 100.,.1 ,-0.1, 4,60," ACCELERATION (G)              ",
     * "  TIME (SEC)   ","                ",200,2000)

       STOP
       END

      subroutine cycle
C     MAIN PROGRAM
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      COMMON /SLOW/BSOC,BSOC1,BSOC2,TAMB,TBATT,TENG,TEM1,TEM2
```

```
      COMMON /ELMTR/TREQEM,TEMMAX,TEMMIN,CARM,CARMRQ,
     *CFLD,CFLDRQ,EARM,EFLD,EFLDRQ
      COMMON/HENGN/TREQHE,THEMAX,THEOPT,
     * THEMIN,SFC,PMAN,OTH
      COMMON /STATUS/ ICOND, KNT, ICHG

C     MAIN PROGRAM PAGE 2
C
      KOUNT = 1
    1 CONTINUE
C     CALL CHECKING ROUNTINE
CC    CALL CHECK
C     CONV : DATA CONVERSION TO ENG'G UNIT
CC    CALL CONV
C     ENG'G UNIT (MKS) BUT VEL IS KM/HR, RPM
C     LOOK UP TABLE GIVE TREQ, TEM MAX, MIN, THE MAX MIN OPT
      CALL TABLE
C     WRITE(1,111)
C 111 FORMAT(" JUST AFTER TABLE")
C     FLAG SETTING
      IF(TREQ.LT.0.)GO TO 10
      IFLAG(7)=0
      IFLAG(8)=0
C     CALL FLAGST
C     VMODE SETTING
 10   CALL VMODE
C  TEMPORARY REGENERATION SIMULATION
      IF(PTREQ.GT.-5.)GO TO 13
      CALL RGB1
      GO TO 40
C  **********************************
C     CALL
   13 IF (VVH.LT.VMOD-5.) GO TO 20
      IF (VVH.GT.VMOD) GO TO 30
      IF (IFLAG(3).GE.1)GO TO 6
      CALL EMMODE
      GO TO 40
    6 CALL HEMODE
      GO TO 40
   20 CALL EMMODE
      GO TO 40

   30 CALL HEMODE
   40 IF (IFLAG(8).GE.1) GO TO 45
      IF(IFLAG(7).GE.1) CALL RGB1
      GO TO 50
   45 CALL RGB2
      GO TO 50
C     ACTUAL HE AND EM POWER SETTING
C     CALL ENGINE
C     CALL MOTOR
C     CALL INSTMT
   50 IF (KOUNT.GT.1000) GO TO 200
      KOUNT = KOUNT + 1
CCC   GO TO 1:REMOVEéééé
```

```
      RETURN
C     SCAN SLOW PARAMETER
C 200 CALL SCAN2
  200 CONTINUE
C     CALL CONV2
      KOUNT = 1
CCC   GO TO 1
      RETURN
CCC   STOP
      END

      SUBROUTINE HEMODE
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      COMMON /SLOW/BSOC,BSOC1,BSOC2,TAMB,TBATT,TENG,TEM1,TEM2
      COMMON /ELMTR/TREQEM,TEMMAX,TEMMIN,CARM,CARMRQ,
     *CFLD,CFLDRQ,EARM,EFLD,EFLDRQ
      COMMON/HENGN/TREQHE,THEMAX,THEOPT,
     * THEMIN,SFC,PMAN,OTH
      COMMON /STATUS/ ICOND, KNT, ICHG

      IFLAG(2) = 0
      IFLAG(3) = 1
      IF (BSOC.LT.0.28) GO TO 1000
      IF (TREQ.LE.THEMAX) GO TO 100
   20 CALL DELAY (2,20)
      IF (ICHG.LE.0) GO TO 999
      TREQEM = TREQ - THEMAX
      TREQHE=THEMAX
      IFLAG(11) = 1
      RETURN
  100 IF (TREQ.GT.0.) GO TO 200
      CALL DELAY (2,100)
      IF (ICHG.LE.0.) GO TO 999
      TREQHE = 0.
      TREQEM=0.
      GO TO 999
  200 IF (TREQ.GE.THEMAX * .95) GO TO 230
      IF(TREQ.LT.THEMAX*.9)IFLAG(11)=0
      GO TO 250
  230 IFLAG(11) = 1
  250 IF (TREQ.LE.THEMIN * .5) GO TO 700
  300 IF (TREQ.GE.THEMIN * 0.8) GO TO 400
      IF (IFLAG(6).GE.1.OR.IFLAG(12).GE.1) GO TO 500
      GO TO 750
  400 IF (IFLAG(6).GE.1.OR.IFLAG(12).GE.1) GO TO 500
      CALL CLEGG
  500 CALL DELAY (2,500)
      IF (ICHG.LE.0) RETURN
      TREQHE = TREQ
      TREQEM=0.
      GO TO 9999
  700 IF (IFLAG(6).GE.1) CALL CLCUT
  750 CALL DELAY (2,750)
      IF (ICHG.LE.0) RETURN
```

```
      TREQHE = 0.
      TREQEM = 0.
      RETURN
 1000 IF (BSOC.LT.0.25) GO TO 2000
      IF (TREQ.LT.THEOPT * 0.8) GO TO 1500
      IF (TREQ.GT.THEOPT) GO TO 1300
 1050 IF (IFLAG(13).GE.1) GO TO 1100
      CALL DELAY (2,1050)
      IF (ICHG.LE.0) RETURN
      TREQHE = TREQ
      TREQEM=0.
      RETURN
 1100 CALL DELAY (2,1100)
      IF (ICHG.LE.0) RETURN
      TREQHE = THEOPT
      TREQEM = TREQ - THEOPT
      RETURN
 1300 IF (TREQ.GT.THEMAX) GO TO 20
      CALL DELAY (2,1300)
      IF (ICHG.LE.0) RETURN
      TREQHE = TREQ
      TREQEM = 0.
      RETURN
 1500 IF (TREQ) 1520, 1520, 1550
 1520 CALL DELAY (2,1520)
      IF (ICHG.LE.0) RETURN
      TREQHE = 0.
      TREQEM = 0.
      RETURN
 1550 IF (IFLAG(13).GE.1) GO TO 1600
C     CALL SPCHG
 1600 IF (TREQEM.GE.TEMMIN) GO TO 1650
      CALL DELAY (2,1600)
      IF (ICHG.LE.0) RETURN
      TREQHE = THEOPT
      TREQEM = TREQ - THEOPT
      RETURN
 1650 CALL DELAY (2,1650)
      IF (ICHG.LE.0) RETURN
      TREQEM = TEMMIN
      TREQHE = TREQ - TEMMIN
      RETURN
 2000 IFLAG(14) = 1
      IFLAG(16) = 1
      IFLAG(15) = 0
      IFLAG(17) = 0
      IF (TREQ) 2020, 2020, 2100
 2020 CALL DELAY (2,2020)
      IF (ICHG.LE.0) RETURN
      TREQHE = 0.
      TREQEM = 0.
      IF (IFLAG(6).GE.1) CALL CLCUT
      RETURN
 2100 IF (TREQ.LT.THEMAX * 0.8) GO TO 2500
      IF (TREQ.GT.THEMAX) GO TO 2300
```

```
 2150 IF (TREQ.LT.THEMAX * .95) GO TO 2170
      IFLAG(11) = 1
      GO TO 2200
 2170 IF (TREQ.LT.THEMAX * .92) IFLAG(11) = 0
 2200 IF (IFLAG(13).GE.1) GO TO 2700
      CALL DELAY (2,2200)
      TREQHE = TREQ
      TREQEM = 0.
      RETURN
 2300 CONTINUE
C2300 IF (IFLAG(13).GE.1) CALL PSCHG
C     IF (IFLAG(14).GE.1) IFLAG(14) = 0
      IFLAG(14) = 0
      GO TO 20
 2500 IFLAG(11) = 0
      IF (IFLAG(13).GE.1) GO TO 2700
C     CALL SPCHG
 2700 IF (TREQEM.LT.TEMMIN) GO TO 2720
      CALL DELAY (2,2700)
      IF (ICHG.LE.0) RETURN
      TREQHE = THEMAX
      TREQEM = TREQ - THEMAX
      RETURN
 2720 CALL DELAY (2,2720)
      IF (ICHG.LE.0) RETURN
      TREQEM = TEMMIN
      TREQHE = TREQ - TEMMIN
 9999 RETURN
  999 RETURN
C     END TEMPORARY
      END

      SUBROUTINE EMMODE
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      COMMON /SLOW/BSOC,BSOC1,BSOC2,TAMB,TBATT,TENG,TEM1,TEM2
      COMMON /ELMTR/TREQEM,TEMMAX,TEMMIN,CARM,CARMRQ,
     *CFLD,CFLDRQ,EARM,EFLD,EFLDRQ
      COMMON/HENGN/TREQHE,THEMAX,THEOPT,
     * THEMIN,SFC,PMAN,OTH
      COMMON /STATUS/ ICOND, KNT, ICHG

      IFLAG(3) = 0
      IFLAG(2) = 1
      IF (TREQ.GT.TEMMAX) GO TO 1000
      IF (TREQ.GE.TEMMAX * .95) IFLAG(11) = 1
CCC   ELSE IFLAG(11) = 0
      IF (TREQ.GT.0) GO TO 80
      TREQEM = 0.
      TREQHE = 0.
      GO TO 999
   80 IF (RNHE.GT.300.) GO TO 200
      TREQEM = TREQ
      TREQHE = 0.
      GO TO 9999
```

```
  200 IF (TREQ.LT.THEMIN) GO TO 300
C     CLUTCH DISENGAGE
      IFLAG(5) = 1
      IFLAG(4) = 0
      TREQEM = TREQ
      TREQHE = 0.
      GO TO 9999
  300 IF (TREQ.GE.THEOPT) GO TO 400
      TREQHE = TREQ
      TREQEM = 0.
      GO TO 9999
  400 TREQHE = THEOPT
      TREQEM = TREQ-THEOPT
      GO TO 9999
 1000 TREQEM = TREQ - THEOPT
      IFLAG(11) = 1
      IF (RNHE.GT.300.OR.IFLAG(12).GE.1) GO TO 1100
      IF (VVH.GT.7) CALL CLEGG
 1100 TREQHE = THEOPT
      IF (TREQ.GT.THEOPT + TEMMAX) GO TO 1200
      GO TO 9999
 1200 TREQEM = TEMMAX
      TREQHE = TREQ - TEMMAX
 9999 RETURN
  999 RETURN
      END


      SUBROUTINE TABLE
C     DIMENSION ACCG(200),VVV(200),
C    *DIST(200)
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      COMMON /SLOW/BSOC,BSOC1,BSOC2,TAMB,TBATT,TENG,TEM1,TEM2
      COMMON /ELMTR/TREQEM,TEMMAX,TEMMIN,CARM,CARMRQ,
     *CFLD,CFLDRQ,EARM,EFLD,EFLDRQ
      COMMON/HENGN/TREQHE,THEMAX,THEOPT,
     * THEMIN,SFC,PMAN,OTH
      COMMON /STATUS/ ICOND, KNT, ICHG

C       TREQ AND
C         TEM  MAX,  MIN,  THE MAX,  MIN,  OPT ARE GIVEN IN  THIS
C     *   ROUTINE.
        DIMENSION ATEMMX(20), ATEMMN(20), ARNEM(20), ATHEMX(20),
     *  ATHEOP(20),ATHEMN(20),ARNHE(20)
        DATA ATHEMX/5.,5.,6.6,7.4,7.78,7.88,7.86,7.84,
     *  7.83, 7.62, 7.24, 6.7, 6.0, 5., 4., 3., 2., 0., 0., 0./
        DATA ATHEOP/4.,4.,4.6,4.8,4.9,5.05,5.1,5.13,
     *  5.15,5. ,4.45,4.05,3.85,3.7,3.55,3.45,3.,0.,
     *  0.,0./
        DATA ATHEMN/2.,2.5,2.75,2.97,3.13,3.22,3.28,3.3,
     *  3.3,3.25,3.1,2.85,2.3,1.8,1.,1.,1.,0.,0.,0./
C       TEMPORARY TEMMIN
        DO 5  N = 1, 20
        IF(N.LE.3)ATEMMN(N)=0.
```

```
      ATEMMN(N)=-5.5
    5 IF(N.GT.7)ATEMMN(N)=-35./FLOAT((N-1))
      ATEMMN(7)=-4.
      ATEMMN(3)=-1.
C   TEMPORARY CALCULATION OF RNEM
      RNEM=WI*RTO
      DO 10  N = 1, 20
      ARNEM(N) =500. *FLOAT((N-1))
   10 ARNHE(N)=500.*FLOAT((N-1))
      DO 20  N = 1, 20
   20 IF (RNEM.LE.ARNEM(N)) GO TO 30
      GO TO 9999
   30 CALL INTRP (TEMMIN, N, ATEMMN, ARNEM, RNEM)
C      write(1,106)
C 106  FORMAT(1H ,"RIGHT AFTER '30' INTABLE")
      WII=WI*RTO
      CALL TEMMX (TMAX, WII)
      TEMMAX=TMAX*RTO
      DO 50  N = 1, 20
C     WRITE(1,108)
C 108  FORMAT(1H ,"IN DO LOOP 50")
   50 IF (WI.LE.ARNHE(N)) GO TO 80
      GO TO 9999
   80 CALL INTRP (THEMAX, N, ATHEMX, ARNHE, WI)
      CALL INTRP (THEMIN, N, ATHEMN, ARNHE, WI)
      CALL INTRP (THEOPT, N, ATHEOP, ARNHE, WI)
      GO TO 200
 9999 IF (IFLAG (20).GE.1) IFLAG(21) = 1
      IFLAG(20) = 1
      GO TO 1000
C     CALCULATE % TREQ = PTREQ & TREQ
  200 A = 1. + WI/6000.
      PTREQ = (OACC - 100.) * A + 100.
      IF(PTREQ.GT.100.)PTREQ=100.
C     CALCULATE MAX TOTAL TORQUE
      TTOT = THEMAX + TEMMAX
      TREQ = TTOT * PTREQ/100.
 1000 RETURN
      END
      SUBROUTINE INTRP (Y, N, YY, XX, X)
      DIMENSION YY(20), XX(20)
      IF(N.LE.1)GO TO 40
      N2=N-1
      DIFY = YY(N) - YY(N2)
      DIFX = XX(N) - XX(N2)
      IF(DIFX.EQ.0.)GO TO 50
      Y = YY(N-1) + DIFY * (X - XX(N2))/DIFX
C     ALWAYS ARRANGE DATA SO THAT XX(N2) < XX(N)
C      WRITE(1,410)
C 410  FORMAT(1H ,"INTERP CALLED & EXECUTED")
      RETURN
   40 Y=YY(1)
      RETURN
   50 WRITE(1,100)
  100 FORMAT(1H ,"ERROR;DIFX BECAME ZERO")
```

```
      RETURN
      END
      SUBROUTINE TEMMX (TEMMAX, WI)
C     DETERMINES TEMMAX (KG-M)
      TSTAL1 =  8.43
      TSTAL2 = 6.714
C     WRITE(1,105)
C 105 FORMAT(1H ,"IN TEMMAX BEFORE IF'S")
      IF (WI.LE.2550.) GO TO 10
C     IF (WI.LE.3200.) GO TO 20
      TEMMAX = 21488./WI
C   21488.  :3OHP HYPERBOLIC LINE
      RETURN
   10 TEMMAX = TSTAL1
      RETURN
   20 TEMMAX = TSTAL2
C     WRITE(1,460)
C 460 FORMAT(1H ,"TEMMX CALLED")
      RETURN
      END
      SUBROUTINE DRAG(V,W,A,CD,DRG,HP)
      VS=V/3.6
      RHO=1.2262/9.806
      AD=RHO*VS**2*A*CD/2.
C               RR;ROLLING RESISTANCE
      RR=W*(.012+1.88E-5*V)
      DRG=RR+AD
      HP=VS*DRG/75.
      RETURN
      END

      SUBROUTINE DELAY(N,IST)
      COMMON /STATUS/ ICOND,KNT,ICHG
      ICHG=0
      IF(ICOND.EQ.IST)GO TO 10
      KNT=0
      ICOND=IST
   10 KNT=KNT+1
      IF(KNT.GE.N)ICHG=1
      ICOND=IST
      IF(KNT.GE.32766)KNT=20
      RETURN
C       N;NUMBER OF CYCLES FOR DELAY:LESS THAN 20
C     IST;PARAMETER TO IDENTIFY FROM WHERE THIS WAS CALLED
C    ICHG;INDICATES I TRANSITION SHOULD TAKE PLACE:1:CHANGE
      END

      SUBROUTINE VMODE
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      COMMON /SLOW/BSOC,BSOC1,BSOC2,TAMB,TBATT,TENG,TEM1,TEM2
      VC=64.
      VMOD=VC
```

```
      IF(BSOC.LT.0.4)VMOD=VC*(1.+2.5*(BSOC-.4))
      RETURN
      END

      SUBROUTINE CLEGG
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      IFLAG(6)=1
      IFLAG(4)=1
      IFLAG(5)=0
      RETURN
      END

      SUBROUTINE CLCUT
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      IFLAG(6)=0
      IFLAG(4)=0
      IFLAG(5)=1
      RETURN
      END

      FUNCTION TRANS(OACC,INDAC)
      TRANS=50.*OACC+700.
      IF(OACC.GT.90.)TRANS=5200.
      IF(OACC.LT.20.)TRANS=1700.
      IF(INDAC.LT.0) TRANS=TRANS-500.
      RETURN
      END

      SUBROUTINE RGB1
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      COMMON /SLOW/BSOC,BSOC1,BSOC2,TAMB,TBATT,TENG,TEM1,TEM2
      COMMON /ELMTR/TREQEM,TEMMAX,TEMMIN,CARM,CARMRQ,
     *CFLD,CFLDRQ,EARM,EFLD,EFLDRQ
      COMMON/HENGN/TREQHE,THEMAX,THEOPT,
     * THEMIN,SFC,PMAN,OTH
      COMMON /STATUS/ ICOND, KNT, ICHG
      IFLAG(7)=1
      IF(IFLAG(6).GE.1)CALL CLCUT
C  TEMPORARY REGENE
      TREQEM=TEMMIN
      TREQHE=0.
      RETURN
      END


      SUBROUTINE RGB2
      COMMON /GEN/KOUNT,VMOD,WI,RTO,PTREQ
     * ,RNEM,RNHE,OACC,TREQ,VVH,IFLAG(30)
      COMMON /SLOW/BSOC,BSOC1,BSOC2,TAMB,TBATT,TENG,TEM1,TEM2
      COMMON /ELMTR/TREQEM,TEMMAX,TEMMIN,CARM,CARMRQ,
     *CFLD,CFLDRQ,EARM,EFLD,EFLDRQ
      COMMON/HENGN/TREQHE,THEMAX,THEOPT,
```

```
     * THEMIN,SFC,PMAN,OTH
       COMMON /STATUS/ ICOND, KNT, ICHG
       IFLAG(8)=1
       IF(IFLAG(6).GE.1)CALL CLCUT
C  TEMPORARY REGENERATION
       TREQEM=TEMMIN*1.5
       TREQHE=0.
       RETURN
       END

C   DUMMY MAIN
C      DIMENSION X(200),Y(200)
C      CHARACTER*32 TITLE
C      CHARACTER*16 XTIT,YTIT
C      TITLE=" T115 HYBRID ACCELERATION   "
C      XTIT= "  TIME  (SEC)"
C      YTIT= "  SPEED (K/HR)  "
C      DO 10 I=1,200
C      X(I)=FLOAT(I)/5.
C      Y(I)=COS(X(I)/3.)*50. +50.
C  10 CONTINUE
C      CALL RGRAPH(X,Y,200,200.,4.,0.,10,
C     * 200.,10.,0.,10,0," T115 HYBRID ACCELERATION       ",
C     * " TIME (SEC)     "," SPEED (KM/HR)  " )
C
C      STOP
C      END

       SUBROUTINE RGRAPH(XARAY,YARAY,N,XINT,XINC,XSTT,NDIVX
     * ,YINT,YINC,YSTT,NDIVY,IMARK,TITLE,XTIT,YTIT,IXOF,IYOF)
       DIMENSION XARAY(200),YARAY(200)
      CHARACTER*32 TITLE
      CHARACTER*16 XTIT,YTIT
C      IXOF=200
C      IYOF=200
       SCALEX=XINT/XINC
       SCALEY=YINT/YINC

       IMK=IABS(IMARK)
       IXST=IXOF+NDIVX*XINT+((IMK+1)/20-1)*150
       IF(IMK.GE.20) GO TO 11

       CALL AXIS(1,XINT,XINC,XSTT,NDIVX,IXOF,IYOF,XTIT)
   11  CALL AXIS(0,YINT,YINC,YSTT,NDIVY,IXOF,IYOF,YTIT)
   12  WRITE(4,440)
  440  FORMAT(" QO")
       GO TO 14
   13  CALL AXIS2(IMARK,YINT,YINC,YSTT,NDIVY,IXST,IYOF,YTIT)
   14  CONTINUE

       DO 20 I=1,N
       IXLOC=IFIX((XARAY(I)-XSTT)*SCALEX)+IXOF
       IYLOC=IFIX((YARAY(I)-YSTT)*SCALEY)+IYOF
       IF(I.EQ.1)GO TO 15
       GO TO 25
```

```
   15  WRITE(4,400)IXLOC,IYLOC
  400  FORMAT(" M",I5,",",I5)
       GO TO 30
   25  WRITE(4,401)IXLOC,IYLOC
  401  FORMAT(" D",I5,",",I5)

   30  CONTINUE
C  30  IF(IMARK.GT.0) WRITE(4,402)IMARK
C 402  FORMAT(" N",I2)

   20  CONTINUE
C      IF(IMK.GE.20)GO TO 999

       IYLOC=IYOF+NDIVY*IFIX(YINT)-100
       IXLOC=IXOF+NDIVX*IFIX(XINT)/2-650
       WRITE(4,470)IXLOC,IYLOC
  470  FORMAT(" M",I5,",",I5)
       WRITE(4,480) TITLE
  480  FORMAT(" P",A32)
       WRITE(4,490)
  490  FORMAT(" H"   )
  999  RETURN
       END

       SUBROUTINE AXIS(IND,RINT,RINC,RSTT,NDIV,IXOF,IYOF,TIT)
       CHARACTER*16 TIT
       WRITE(4,400)IXOF,IYOF
  400  FORMAT(" M",I5,",",I5)

       INT=IFIX(RINT)
       INC=IFIX(RINC)

       WRITE(4,401)IND,INT,NDIV
  401  FORMAT(" X",     I1,",",I3,",",I2)

       WRITE(4,402)
  402  FORMAT(" S2")

       IYLOC=IYOF-45
       IXLOC=IXOF-120
       MM=NDIV+1



       DO 30 I=1,MM
       IF(IND.EQ.1)IXLOC=IXOF-85+(I-1)*INT
       IF(IND.EQ.0)IYLOC=IYOF- 8+(I-1)*INT

       SCALE=RSTT+FLOAT(I-1)*RINC
       WRITE(4,405) IXLOC,IYLOC
  405  FORMAT(" M",I5,",",I5)

       WRITE(4,407)SCALE
  407  FORMAT(" P" ,F6.1)
   30  CONTINUE
```

```
      WRITE(4,410)
  410 FORMAT(" S5")
      IF(IND.EQ.0)GO TO 100
C  XTITLE WRITING
      IXLOC=(IXLOC-IXOF)/2+IXOF-400
      IYLOC=IYLOC-85
      WRITE(4,413)IXLOC,IYLOC
  413 FORMAT(" M",I5,",",I5)
      WRITE(4,415) TIT
  415 FORMAT(" P",  A16)
      RETURN
C YTITLE WRITING
  100  IYLOC=(IYLOC-IYOF)/2+IYOF-450
      IXLOC=IXLOC-40
      WRITE(4,417)
  417 FORMAT(" Q1")
      WRITE(4,420)IXLOC,IYLOC
  420 FORMAT(" M",I5,",",I5)
      WRITE(4,430)    TIT
  430 FORMAT(" P",   A16)

      WRITE(4,490)
  490 FORMAT(" H")
      RETURN
      END

      SUBROUTINE AXIS2(IND,RINT,RINC,RSTT,NDIV,IXOF,IYOF,TIT)
      CHARACTER*16 TIT
      WRITE(4,400)IXOF,IYOF
  400 FORMAT(" M",I5,",",I5)
      WRITE(4,399)IXOF,IYOF
  399 FORMAT(" M",I5,",",I5)
C
C      WRITE(4,398)



      INT=IFIX(RINT)
      INC=IFIX(RINC)
        III=0
      WRITE(4,401)III,INT,NDIV
  401 FORMAT(" X",I1,",",I3,",",I2)

      WRITE(4,402)
  402 FORMAT(" S2")

C     IYLOC=IYOF-45
      IXLOC=IXOF+45
      MM=NDIV+1



      DO 30 I=1,MM
C     IF(IND.EQ.1)IXLOC=IXOF-85+(I-1)*INT
```

```
      IYLOC=IYOF-65+(I-1)*INT

      SCALE=RSTT+FLOAT(I-1)*RINC
      WRITE(4,405) IXLOC,IYLOC
  405 FORMAT(" M",I5,",",I5)

      WRITE(4,406)
  406 FORMAT(" Q1")

      WRITE(4,407)SCALE
  407 FORMAT(" P" ,F6.1)
   30 CONTINUE

      WRITE(4,410)
  410 FORMAT(" S4")

C YTITLE WRITING
  100   IYLOC=(IYLOC-IYOF)/2+IYOF-400
      IXLOC=IXLOC+45
      WRITE(4,417)
  417 FORMAT(" Q1")
      WRITE(4,420)IXLOC,IYLOC
  420 FORMAT(" M",I5,",",I5)
      WRITE(4,430)    TIT
  430 FORMAT(" P",   A16)

      WRITE(4,440)
  440 FORMAT(" Q0")
      write(4,490)
  490 FORMAT(" H")
      RETURN
      END
```

APPENDIX I

I1

HYVEC Simulations of Marathon Parallel Hybrid Design

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A HYVEC simulation of the Marathon Hybrid proposed parallel design was made at General Electric CRD. The results are shown in Figures 1 to 5 attached.

Figure 1. Acceleration Characteristics

The acceleration performance calculated was: -

0 to 48 kph	8 seconds
0 to 80 kph	19 seconds

This performance could be improved slightly (say 1 or 2 seconds) by permitting the motor field to exceed the rated value during short periods as in full throttle accelerations.

Figures 2 to 4 Fuel Economy & Battery Discharge Characteristics

All calculations were done on the U.S. EPA driving cycles (urban and highway). In Figue 2 results are shown for the average fuel economy in urban driving for a VMOD of 96 kph (i.e. all power is provided from electric drive if possible). Fuel economy of at least 3.37 litres per 100 km is projected for daily travel of 80 km or less. Battery charging from the heat engine is not needed until a daily travel of about 95 km. The range is stretched beyond the electric range of about 55 km by reducing VMOD automatically as the battery state-of-charge (SOC) decreases. Cycle-by-cycle fuel economy is shown in Figure 3 for VMOD of 96 kph. Just prior to charging the battery with the heat engine the fuel economy is about 5.9 litres per 100 km at a VMOD of about 16kph (i.e. the vehicle operates as an electric vehicle up to about 16 kph when the battery SOC is 25%). The highway fuel economy (CD = .45) was found to be 5.4 litres per 100 km. The results for a VMOD of 65kph and 95 kph are compared in Figure 4. The reduction in VMOD from 95 kph to 65 kph reduces the minimum litres per 100 km but also stretches the daily urban distance before the need to recharge the batteries from the heat engine to in excess of 120 km.

Figure 5 Electrical Energy Use

The KwH use from the battery is shown in Figure 5. As would be expected the KwH per km net decreases as the VMOD is automatically reduced to stretch the range. It is of interest to note that 68% (on average) of the power (or energy) needed to drive the vehicle comes from the battery during the first 2 Or 3 urban cycles (out to about 40 km daily travel).

Figure 1

Acceleration Characteristic of the Marathon Hybrid

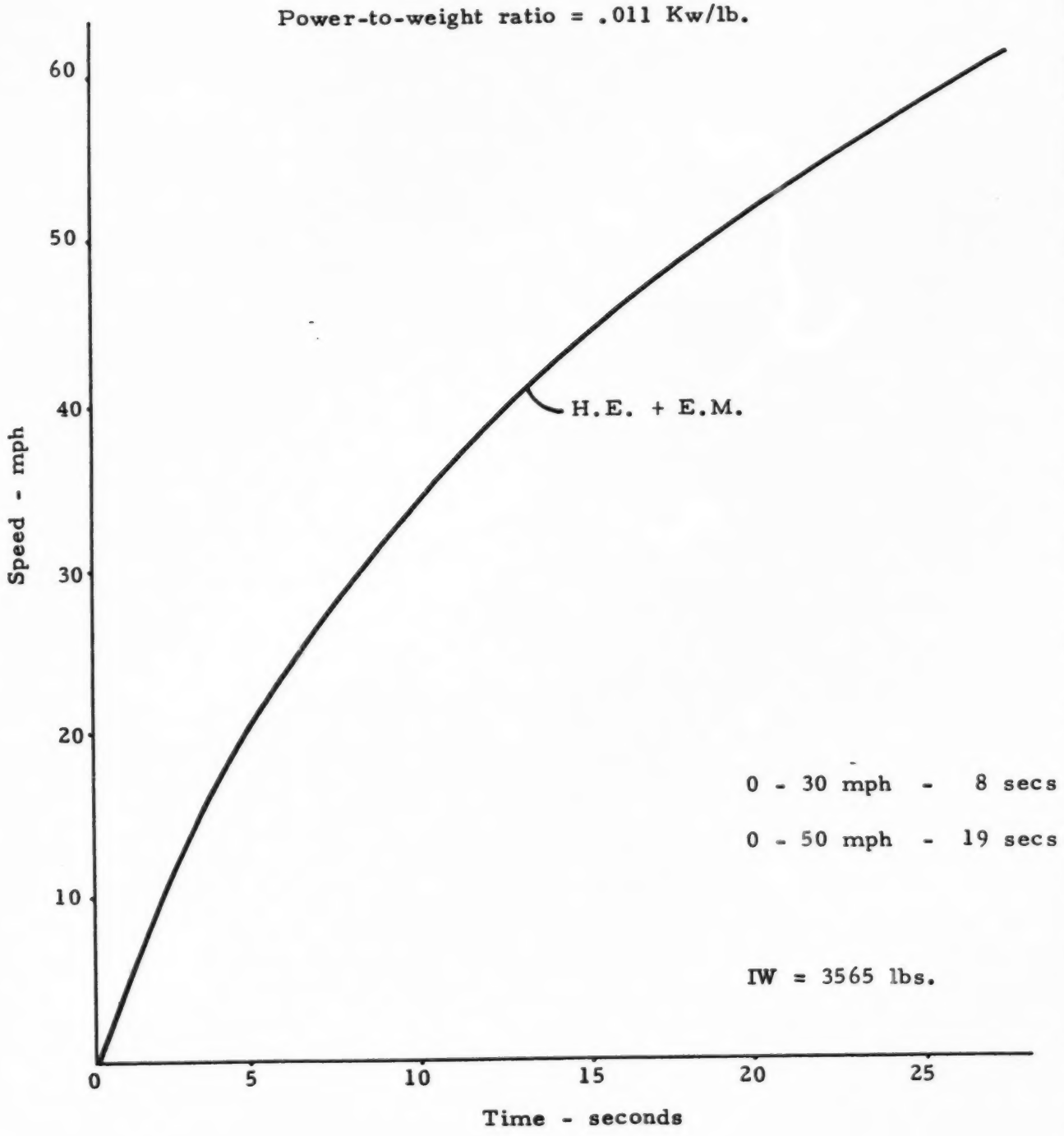


Figure 2

Fuel Economy and Battery Discharge Characteristics of the Marathon Hybrid on the EPA Urban Cycle

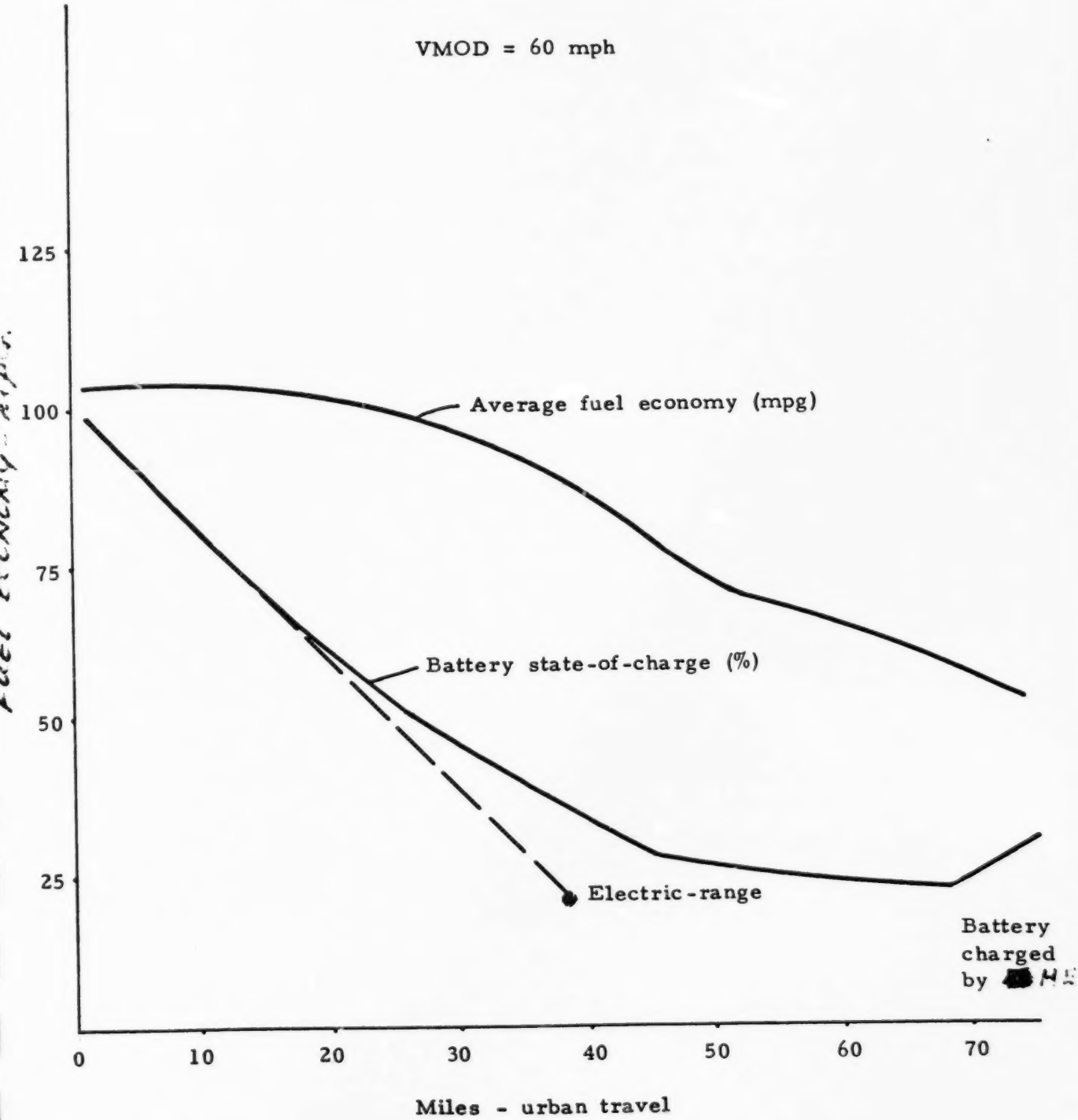


Figure 3

Cycle-by-Cycle Fuel Economy of the Marathon Hybrid

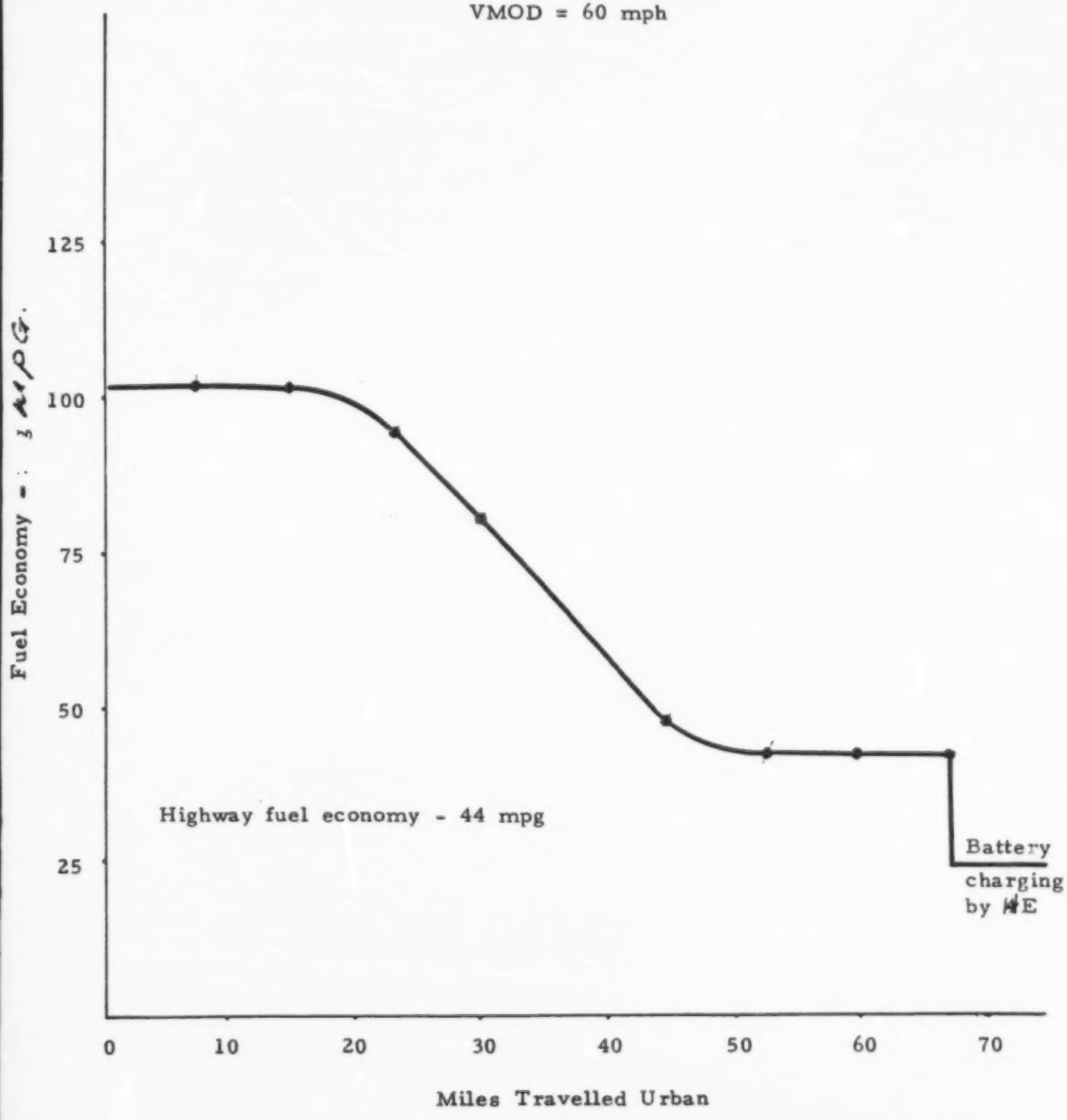


Figure 4

Comparison of Fuel Economy and Battery Discharge Characteristics of the Marathon Hybrid for VM = 40 mph and 60 mph

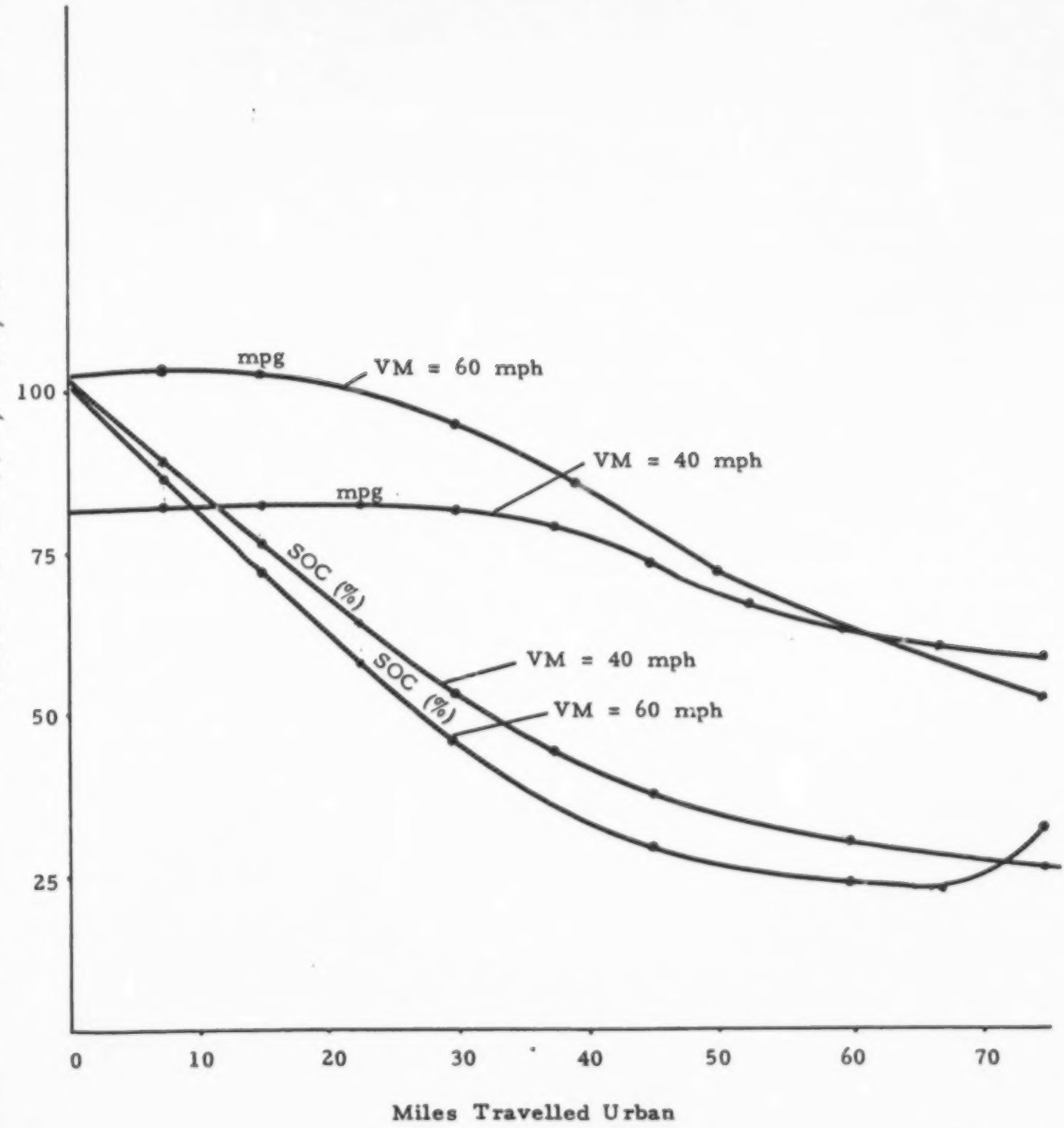
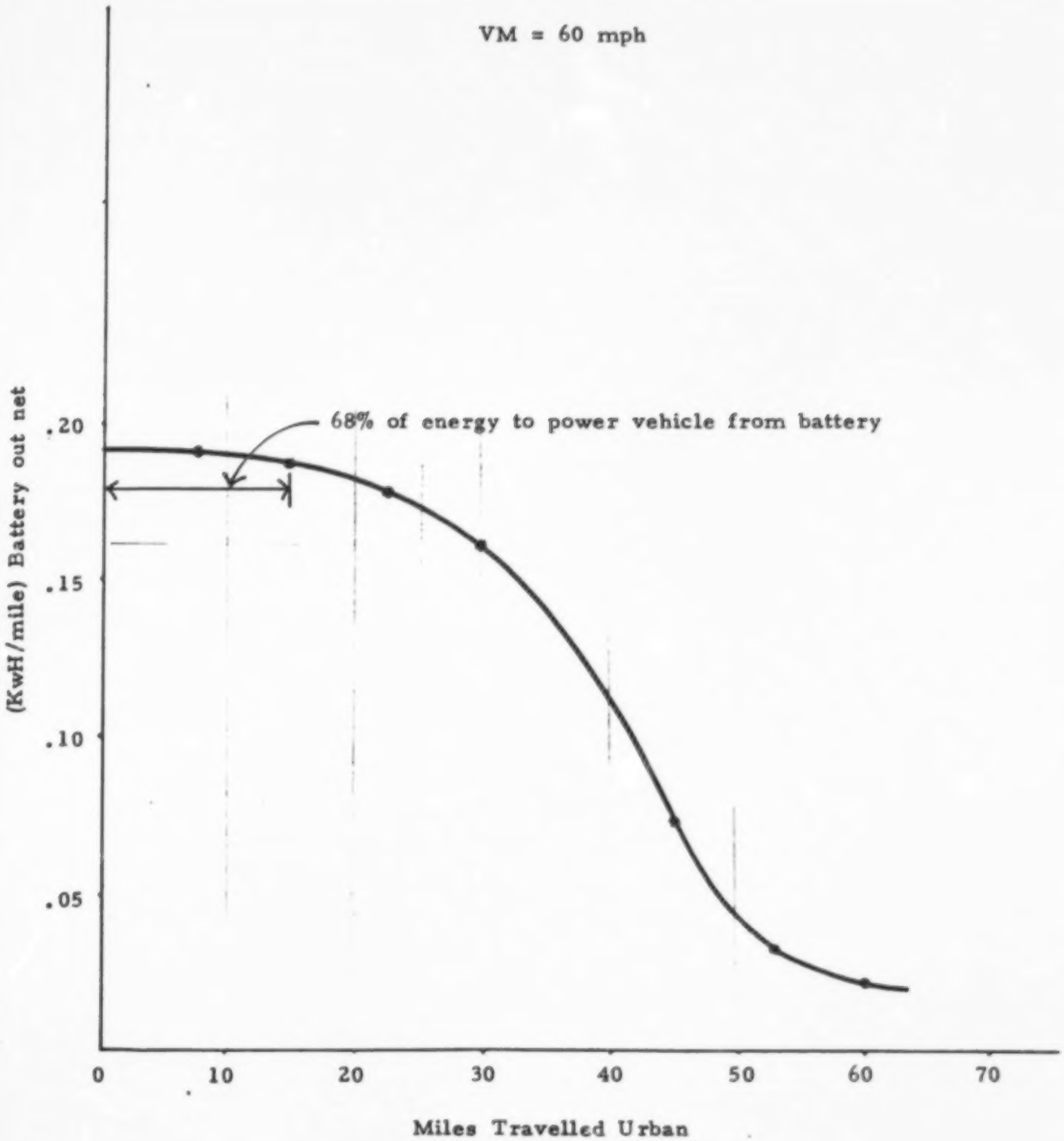


Figure 5

Electrical Energy-Use Characteristics of the Marathon Hybrid



POOR
QUALITY
ORIGINAL